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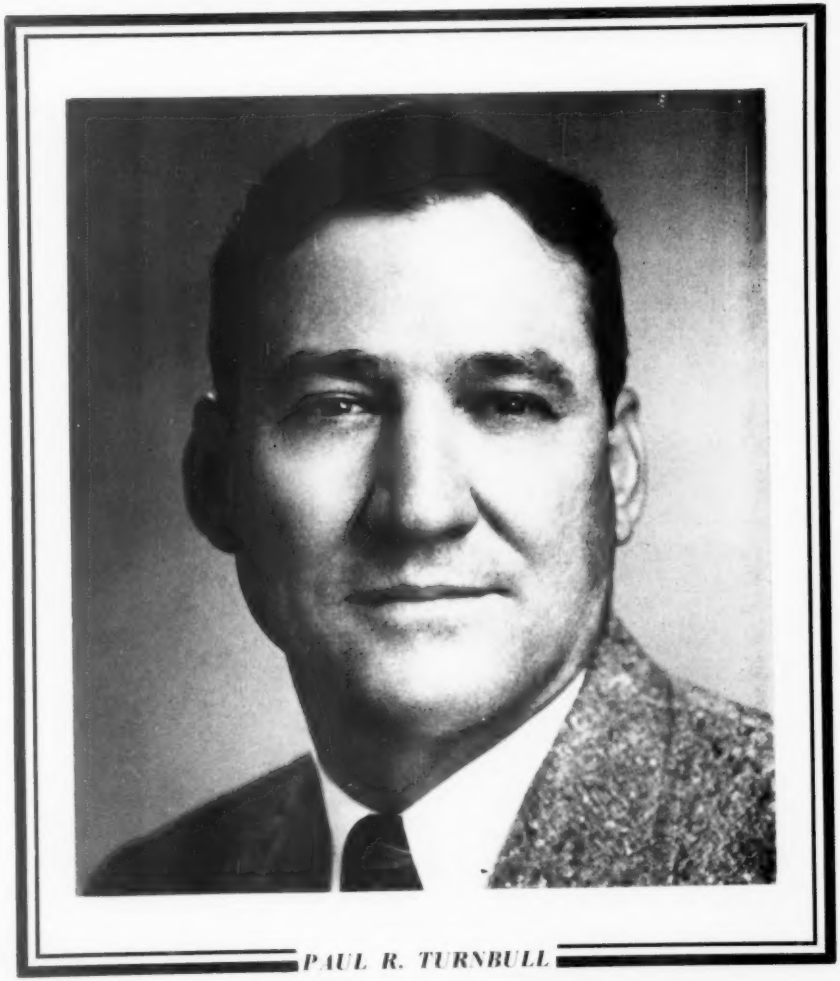
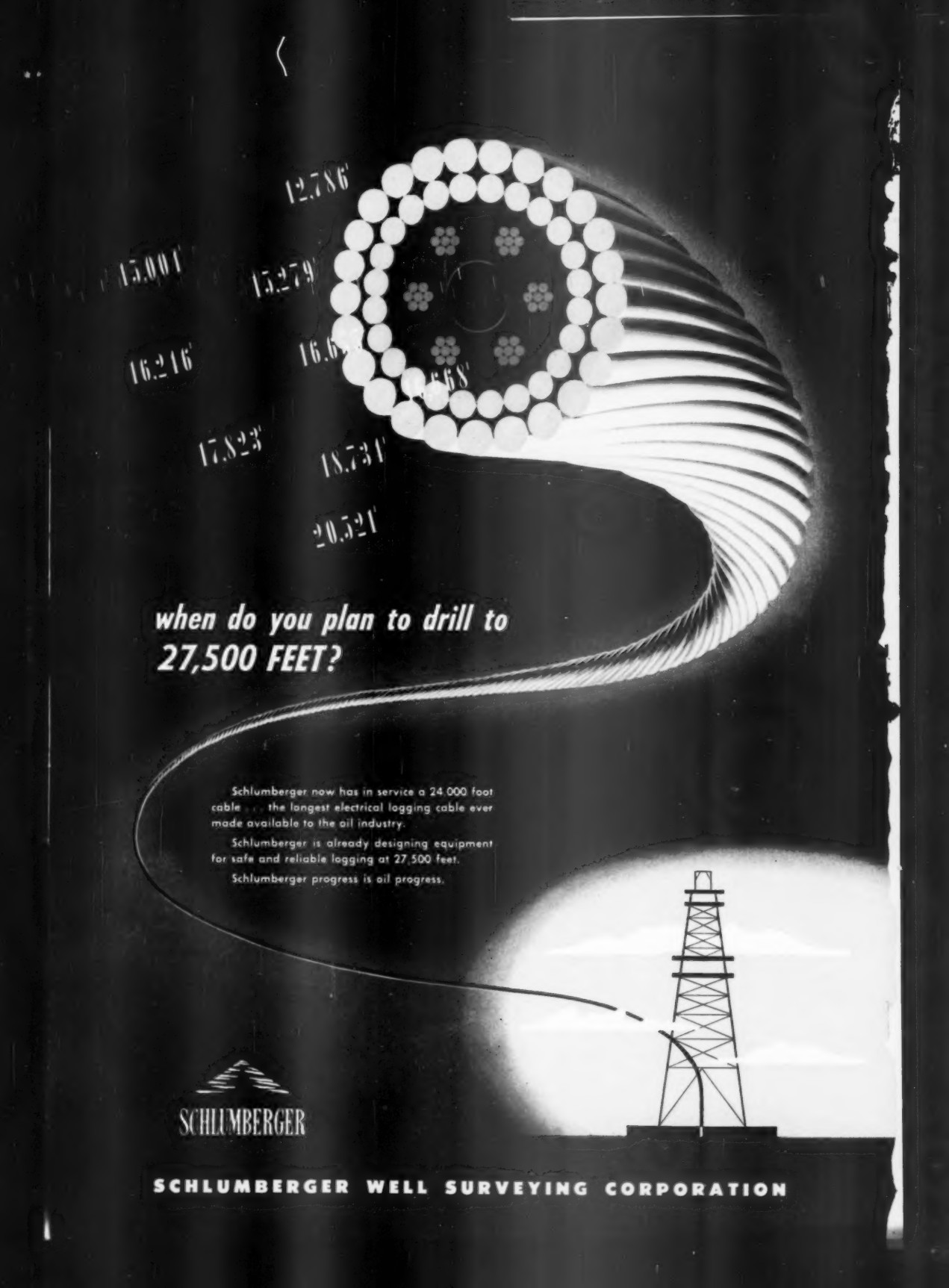
Petroleum Technology



PAUL R. TURNBULL

FEBRUARY, 1952



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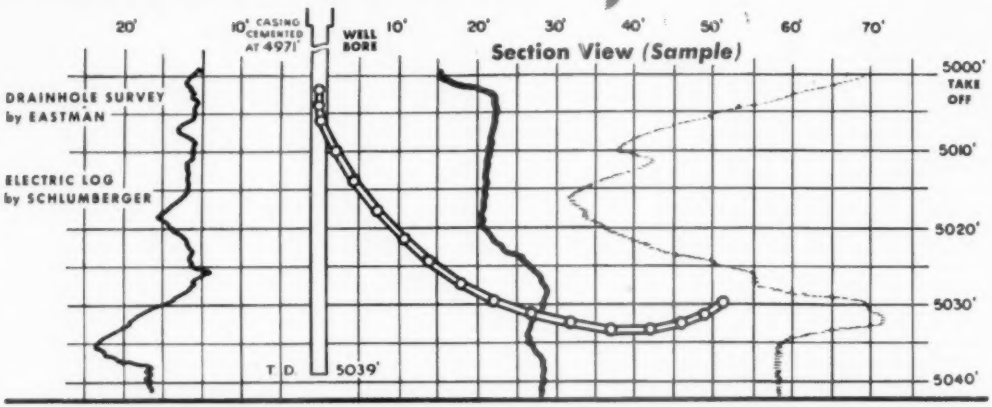

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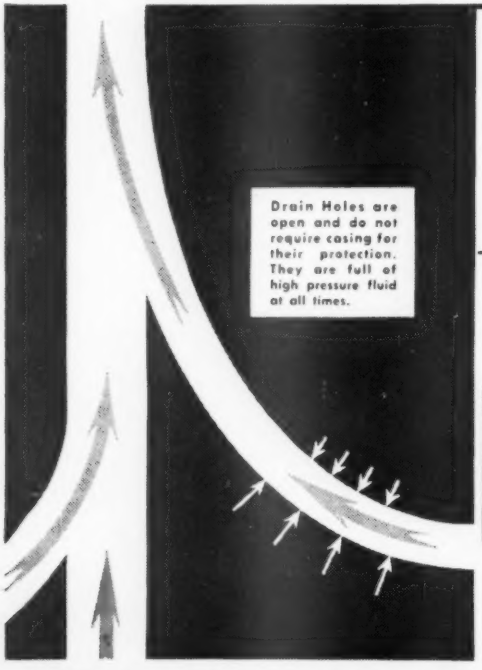

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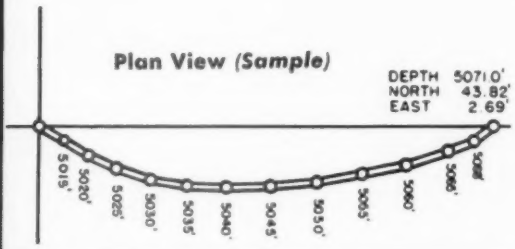

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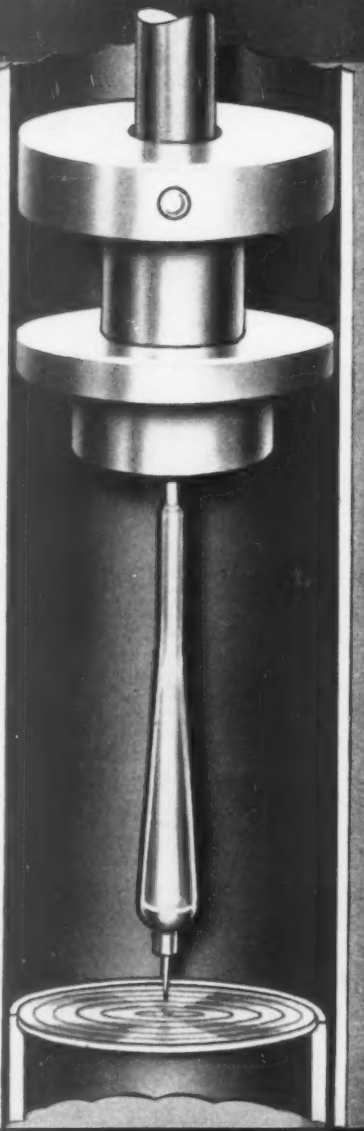

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On the Cover — At the Annual Meeting in New York City this month, Paul R. Turnbull, of the La Gloria Corp. in Corpus Christi, Tex., will be installed as Petroleum Branch Chairman for 1952, taking up the reins from Richard W. French. For a word picture of Paul's Branch and Professional activities, see Page 14, Section 1.

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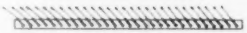

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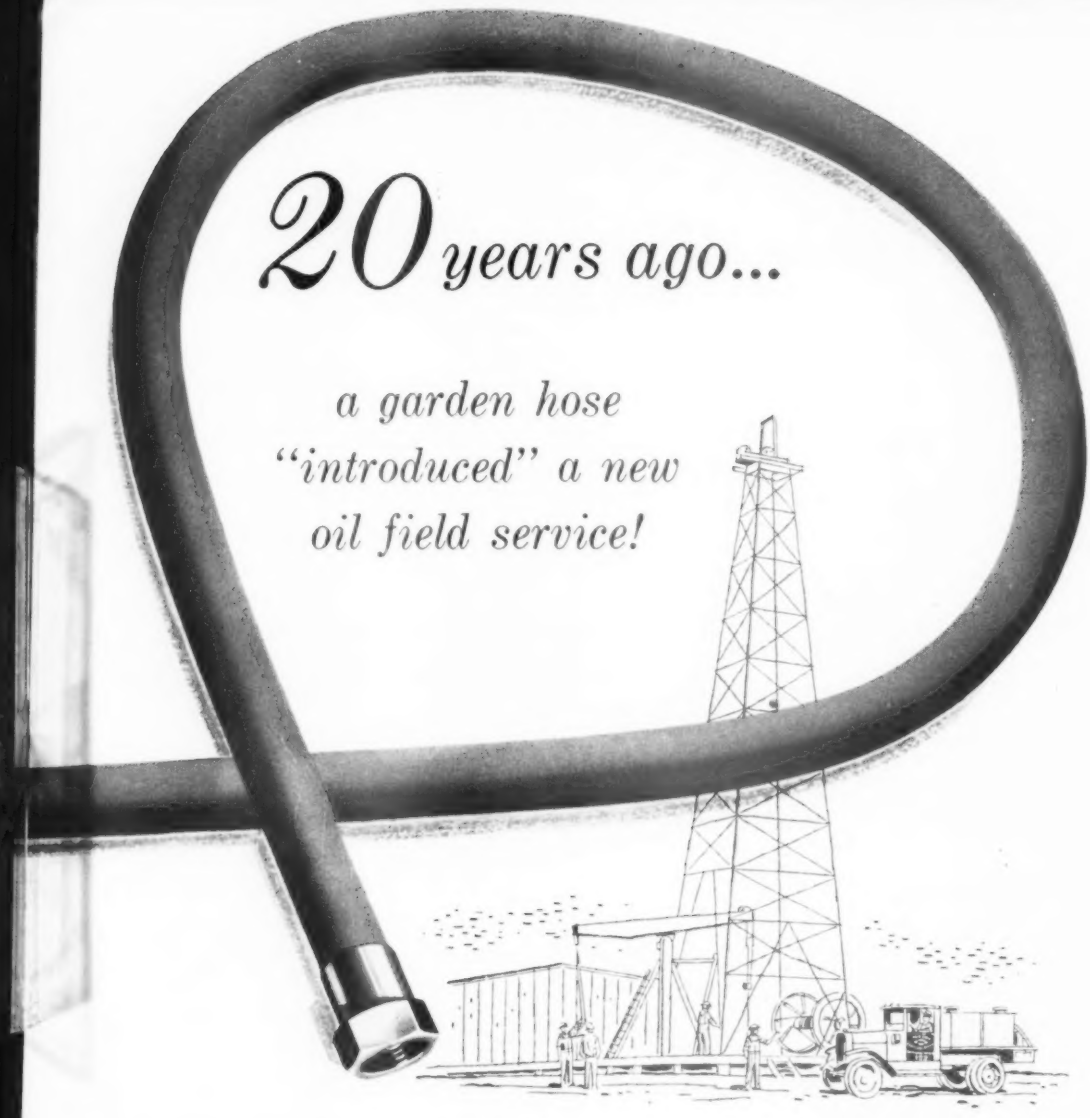

It was just an ordinary forty-foot piece of garden hose. Yet, this was the first piece of equipment used by The Dow Chemical Company to introduce inhibited acid into an oil well in central Michigan. The date, February 11, 1932, marked the *beginning of acidizing service* to the oil industry.

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Today Dowell research continues to cooperate with the industry by providing new materials and new methods to solve oil field problems. Among the many valuable contributions Dowell has made are Selective Acidizing . . . the Electric Pilot Services . . . Perfo-Jet Service with the Glass Gun . . . Plastic Service . . . Jelflake . . . Paraffin Solvents . . . Bulk Inhibited Acid . . . Maintenance Cleaning Service for Heat Exchange Equipment.

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API Standards in Equipment are Now Recognized Throughout the World. Here an API Official Evaluates The Program Begun Domestically in 1923.

International Standardization of Oil Field Equipment

By C. A. Young
American Petroleum Institute
Member AIME

THE standardization of oil field drilling and production equipment, by the Division of Production of the American Petroleum Institute, inaugurated in 1923 as a domestic activity, has expanded to the point where API standards are now recognized as international standards. The oil industry, therefore, has a very substantial stake in the field of international standardization.

There have been some interesting developments affecting the growth and recognition of these standards in foreign countries. The primary factor in this recognition has been the leadership demonstrated by the American oil industry in the development of drilling and production methods and in the application of those methods in foreign fields. The rotary system of drilling, originated and developed in the United States is the more popular, although the cable tool system is still used in many areas both here and abroad. The rotary system is similar to an augur which rotates as it penetrates, as compared to the older drop weight (cable tool) method which chisels and pulverizes as it progresses.

The wide distribution of American equipment abroad carried with it API standards. Eventually many foreign manufacturers became interested in copying American designs, which involved the use of the necessary master gauges on threaded products. A word about the scope of the Institute's standardization program and its administration is necessary here to provide a better understanding of the factors involved in the expansion of its use abroad.

Drilling Tool Connections

This program, similar to those in many other industries, covers both quality and interchangeability. While standards of quality are essential, the interchangeability of threaded and mating parts is of transcendent importance. The maintenance of interchangeability and the selection of sizes and types of threaded connections presented some interesting problems and required considerable study. Pipe, in the form of casing, tubing and drill pipe, is a very vital item in drilling for oil and gas. These tubular products are threaded with the 60° V-thread, both roots and crests being rounded. The threaded connections on accessory equipment in the drill stem, such as tool joints, drill collars, and tool bits, utilize a coarse pitch, steeply tapered thread having a truncated 60° thread form. Prior to API standardization there was no dependable interchangeability between these important connections of different manufacture. The complete chaos on drilling tool connections was solved by the adoption of complete specifications on a selected list of sizes of threads, including specifications on master gauges.

The key to maintaining interchangeability on drilling tools is the maintenance of accuracy of reference master gauges owned by the various manufacturers. This was accomplished under the tutelage and guidance of the U. S. Bureau of Standards. The keystone of the arch was a set of grand master drilling tool gauges deposited with the U. S. Bureau of Standards, with supplementary secondary masters deposited with official testing agencies in the Eastern, Mid-Continent, and Pacific Coast regions of the United States, where manufacturers could test their master gauges at stated intervals. When gauges are beyond stated interchange tolerances, they must be reconditioned. In that way, no manufacturer can depart from this official standard for any great period. Experience has shown that the interval of three years now specified for retesting insures complete protection for maintaining the standards. In the case of pipe threads, grand master gauges are not required as interchangeability can be maintained by direct measurement of the threaded elements of the manufacturers' reference gauges. Annual reports from pipe manufacturers are required on the accuracy of their master gauges. Illustrations of typical master gauges are appended. It can now be stated that every important threaded connection in use in the producing branch has been standardized.

An important part of this international development is the Institute's system of identifying products that meet its specifications. It has an official registered monogram, the use of which is granted to manufacturers under specified conditions. These conditions require a statement from the manufacturer detailing his qualifications and also an affidavit that the monogram will be used only on products which comply with a particular specification, and that material that does not comply will not be so marked. Compliance with API standards and marking privileges is entirely the responsibility of the manufacturer. Policing of compliance is done by the purchaser, either through commercial testing agencies or his own inspectors. There have been instances of non-compliance, which have been promptly rectified by the manufacturer, but there have been no cases of willful non-compliance.

Foreign Compliance

When foreign manufacturers became interested in API standards, the problem of testing and maintaining their master gauges arose. This was solved through the appointment of foreign official certifying agencies which are the counterparts, in their respective countries, of our U. S. Bureau of Standards. Before appointment, the foreign testing agency was required to calibrate a gauge and report on its acuracy. The gauge was then sent to the U. S. Bureau of Standards where it was again calibrated and the results of these two tests then compared. Where differences occurred, they were adjusted by correspondence until there was complete agreement on the accuracy of the equipment and methods of measurement used by both. The U. S. Bureau of Standards is and has always been the

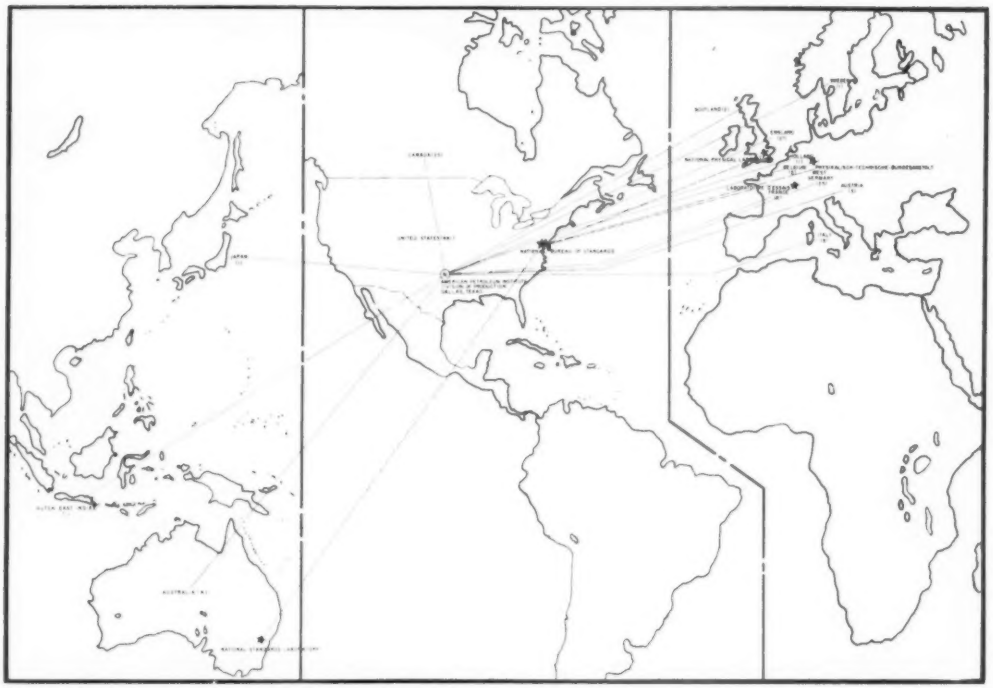


FIG. 1—DISTRIBUTION OF MANUFACTURERS AUTHORIZED TO USE THE API MONOGRAM SHOWING OFFICIAL GAUGE CERTIFYING AGENCIES.

court of last resort on accuracy. Its judgment is final. The oil industry is deeply appreciative of this service from the U. S. Bureau of Standards and gratefully acknowledges the fine spirit of cooperation it has always extended in our work.

This method of interchange testing solved the question of testing gauges owned by foreign manufacturers. Adjustment of differences with the official English laboratory were minor and quickly solved. In other countries, the period of interchange testing required a much long period of time. In one case, the U. S. Bureau of Standards supplied the foreign testing agency with drawings of equipment that had to be built before the Bureau could accept their measurements. Today there are four such foreign testing agencies in Europe and Australia. They are the National Physical Laboratory, Teddington, Middlesex, England; Physikalisch-Technische Bundesanstalt, Braunschweig, (West) Germany; Laboratoire d'Essais du Conservatoire des Arts et Metiers, Paris, France; and National Standards Laboratory, Division of Metrology, Chippendale, New South Wales, Australia.

A system of reports on gauges owned by manufacturers has been adopted and pedigree records are maintained in Dallas on the accuracy of the master gauges owned by each manufacturer who has been authorized to use the API monogram. It is through this system of master gauges, official testing agencies, and systematic reports, that interchangeability is maintained on an international basis.

The use of the Institute's monogram is not confined to threaded connections. It is also used on other products as well, for example, wire rope, derricks, mating pump parts, belting, steel chain and others.

Fig. 1 is a map which illustrates the scope of the API standardization program as indicated by the location of authorized manufacturers and authorized testing laboratories. There are at present 141 manufacturers in the United States, and 115 manufacturers located outside of the United States who have authority to use the API monogram.

Specifications Translated

A substantial number of API specifications are translated into German, French, and Italian. In the English speaking countries, API specifications have been adopted by several of the national standards agencies or have been used as the basis for the promulgation of related standards in which the interchangeability provisions of API specifications have been preserved.

Cooperation with foreign national standards organizations is maintained through the interchange of committee reports, specifications, and other publications. Because of the strategic and economic importance of petroleum, the current activity in drilling and production exceeds that of any prior period and this intensity is reflected in a very widespread participation in our standardization program.

The value of the products made annually to API standards is on the order of $500 million, not taking into account material manufactured and distributed abroad. The savings of this program are incalculable but the fact that the component parts of a drilling rig can be purchased from manufacturers residing in 13 foreign countries and assembled at some distant point to drill an oil well is a practical demonstration of its efficacy. Recently there has been some striking evidence of the value of this program occasioned by the shortage of steel in this country. In the past year several thousand tons of

Geographical Distribution of Manufacturers Authorized to Use the API Monogram

UNITED STATES (441)

	Number
California	95
Colorado	3
Connecticut	5
Delaware	1
Florida	1
Idaho	1
Illinois	13
Indiana	3
Louisiana	6
Kansas	2
Maryland	2
Massachusetts	10
Michigan	17
Minnesota	1
Missouri	12
New Jersey	12
New York	8
Ohio	49
Oklahoma	34
Oregon	4
Pennsylvania	60
Rhode Island	2
Texas	59
Tennessee	6
Utah	2
Virginia	2
Washington	6
West Virginia	16
Wisconsin	8
Wyoming	1

CANADA (21)

	Number
Alberta	1
British Columbia	3
Manitoba	1
Ontario	9
Quebec	7

CONTINENTAL EUROPE (49)

Austria	3
Belgium	2
France	8
Germany	25
Holland	1
Italy	9
Sweden	1

GREAT BRITAIN (39)

England	37
Scotland	2

ASIA (2)

Dutch East Indies	1
Japan	1

AUSTRALIA (4)

New South Wales	4

tubular goods made in England, Germany, Belgium and France, have been imported into the United States and are being used in our domestic drilling operations. This foreign pipe interchanges perfectly with the American product.

The Institute also has been cooperating with the armed services of our government in the development of standards on storage tanks for oil and other products. Petroleum and its products are very important to our armed forces and the probable storage of these products is identical with their use in our domestic economy. During World War II several thousand tanks made to API specifications were used by the armed forces and when the war was over there was a large surplus which was immediately made available to the industry. Recently the Army has indicated a need for a more complete interchangeability on some of the component parts. This detailed interchangeability has been worked out with the Army so that today storage tanks for either the armed forces or domestic use are identical. The savings in producing material of this type for our defense needs without the building of special plants and equipment is apparent.

We are aware that there is an international standardization agency now functioning in an attempt to harmonize and standardize wherever possible on materials and equipment used in the international field. With the present rapid advances in speed in transportation and communication, the need for international standardization will undoubtedly increase and become more and more a necessity. Our reason for presenting this picture in the international field is to make our experiences available to this group in the hope that it might be of some interest and service. We are not attempting to make any suggestions in any way on the future activities of this international group other than to express our willingness to cooperate in any way we can in bringing about a better understanding and greater cooperation in our international relationships. ★

S. E. Buckley Receives Certificate of Service

The Sixth Petroleum Branch Certificate of Service will be awarded to Stuart E. Buckley, chief of production research for Humble Oil and Refining Co., at the Annual Banquet of the Petroleum Branch the night of Feb. 19 in New York City. Last recipients of the award were Joseph B. Umpleby and F. Julius Fohs who were honored in 1949. Buckley's certificate comes at a time when he has just completed the editing of the volume entitled *Petroleum Conservation*. The certificate which he will receive in New York reads:

"In gratitude for his invaluable contributions to petroleum engineering literature culminating in his superb editing of the Doherty Memorial Volume, *Petroleum Conservation*, and for his unselfish and proficient leadership of many Local Section and Branch Committees, with particular reference to his ability to bring into constructive focus many varied and divergent views."

Buckley is a native of Eagle Pass, Tex. He attended the University of Texas at Austin from 1926 to 1933 during which time he received the BS and MS degrees in chemical engineering. In mid-1933, he joined Humble as a roustabout in the Conroe Field, later transferring to the Production Research Dept. Since that time, he has worked with Humble as a research engineer, concerning himself mostly with production problems and oil reservoir behavior. In 1939, he was advanced to assistant head of the department and in 1944 assumed its direction.

Buckley has also been busy in the affairs of the Petroleum Branch. In 1942, he served as chairman of the Gulf Coast Section and was elected to the Petroleum Branch Executive Committee in 1944, serving also as vice-chairman.

STUART E. BUCKLEY

Technical Note 108——

A STUDY OF THE PERMANENCE OF PRODUCTION INCREASES DUE TO HYDRAULIC FRACTURE TREATMENTS

C. R. FAST, STANOLIND OIL AND GAS CO., TULSA, OKLA.

In order to evaluate the ability of a Hydrafrac treatment to effect a sustained increase in well production, data were accumulated on the first 65 wells in 26 fields treated by Stanolind. Since these data were obtained from such a large number of fields, it is felt that individual well or reservoir characteristics do not affect the overall picture, as might be the case if the study were made in one field or one group of wells in a field. These data are tabulated in Table I and plotted on Figs. 1 and 2.

An analysis of Fig. 1 shows that at the end of six months, 75 per cent, or 45, of 60 wells on which data were available showed a sustained production increase. At the end of two years, data were available on 25 wells. Of these, 15 wells, or 60 per cent, showed a sustained production increase. At the end of three years, 55 per cent, or 10, of 18 wells had a production rate greater at that time than before Hydrafrac treatment. The lack of information on additional wells at the end of the third year is primarily a result of the small number of treatments conducted in the early stages of field application of this process. Production data on wells treated more than three years ago are limited to so few wells that they were not considered.

Fig. 2 contains two plots of the production data from the wells surveyed, expressed as per cent of pretreatment production plotted against time in years after treatment. Only the wells showing a sustained increase in production were considered in the upper plot, while all wells on which data were available were considered in the lower plot. The upper curve shows that two years after treatment, the production from these wells was 200 per cent greater than before treatment. Even after three years, these wells were producing at a rate that was 134 per cent of the pre-Hydrafrac production rate. When considering all of the wells treated from which data were available, it may be seen from the lower curve that after two years over 150 per cent of pre-Hydrafrac production was being maintained. The production from these wells did not decline to the pretreatment level until approximately two and three-fourths years after treatment.

The increased production shown on Fig. 2 is all net increased production, since the cost of Hydrafrac treatment of all wells was paid out during the first six months of production not shown on this graph.

An analysis of these data indicates that Hydrafrac treatment is capable of effecting a sustained increase in production. As additional data become available, this study will be continued to determine the duration of the production increase. ★ ★ ★

Manuscript received in the Petroleum Branch office Nov. 26, 1951.

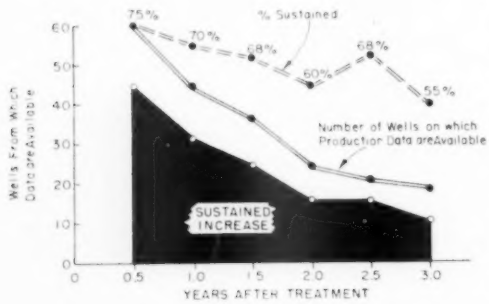


FIG. 1 — PRODUCTION SUSTAINED AFTER HYDRAFRAC.

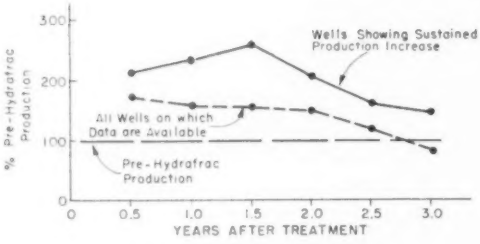

Wells Showing Sustained Production Increase
All Wells on which Data are Available
Pre-Hydrafrac Production
% Pre-Hydrafrac Production
YEARS AFTER TREATMENT

FIG. 2 — PRODUCTION DECLINE AFTER HYDRAFRAC.

Table I

	Time after treatment, years					
	0.5	1.0	1.5	2.0	2.5	3.0
Wells on which data available	60	44	35	25	22	18
Wells showing sustained production increase	45	31	24	15	15	10
Wells showing no sustained production increase	15	13	11	10	7	8
Per cent of reported wells showing sustained production increase	75	70.5	68.6	60	68.2	55.5
Per cent of pre-Hydrafrac production for wells showing sustained increase	210	223	257	203	162	134
Per cent of pre-Hydrafrac production for all wells reported	175	163	161	153	118	83

Baash-Ross News

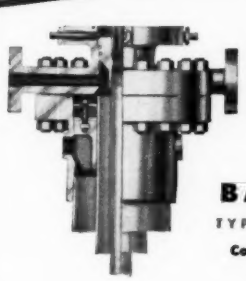
HOUSTON • OKLAHOMA CITY • NEW YORK

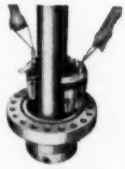
OUR 32nd YEAR

Here's what BAASH-ROSS has done to simplify your well head problems!

THREE BASIC TYPES OF UNITS MEET EVERY OPERATOR'S REQUIREMENTS

For many years Baash-Ross has been a leader in the development of more compact, more efficient Well Head Equipment. And to meet the varied requirements of present-day operations, Baash-Ross now offers three basic types of Head Assemblies—each offering certain vital advantages to save time, space, and money on your development programs . . .





BAASH-ROSS TYPE "UPS" HEADS

Combine Pack-Off And Slips In One Unit

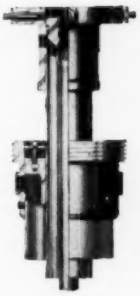
Type "UPS" Heads—a new Baash-Ross development—have the Packing Element and Slips unitized into a *single* hinged assembly that simply w-r-a-p-s around the casing and locks in place with one bolt. As the weight of the casing is placed on the slips, they *automatically* equalize themselves within the bowl to assure exact centering of the casing as well as a uniform grip around the *entire circumference* of the pipe. A few quick turns of a wrench then expands the packing element for a pressure-tight seal.

"UPS" ADVANTAGES INCLUDE . . . (1) No space wasted by threads, grooves or other packer-retaining devices—therefore overall height is reduced to a minimum . . . (2) Elimination of threads, grooves, etc., means a smooth bowl—nothing to become damaged during drilling operations, no need for protective sleeves . . . (3) Since all the slip segments are unitized together, none can set higher or lower than the rest—no risk of crimping the casing, no danger of an unequal grip that may fail in service . . . (4) Slips are set and packing is tightened around casing without stripping and without first cutting the casing. Simplifies installation—saves time!

"UPS" Heads also incorporate the unique Baash-Ross weld-testing feature which permits simultaneously testing the pressure-tightness of *both* casing welds with a gauge and hand pump as part of the installation procedure—or any time later. Any leaks discovered during the life of the well can be quickly sealed off by injecting plastic pack material.

"UPS" Equipment is available in a complete range of sizes . . . for threading or welding to the casing . . . with or without Bases . . . and for use with over a dozen different Tubing Heads Suspensions and Hook-Ups. *It is the ideal solution for a wide range of requirements on medium and low-pressure wells!*

View of Flange installed showing packing arrangement.



BAASH-ROSS TYPE "UPS-DF" HEADS

Offer "UPS" Advantages Plus Demountable Flanges

Type "UPS-DF" Heads combine all the "UPS" advantages with an additional important feature—*Demountable Flanges that can be salvaged after the drilling operations for use on other installations.*

The body, packing and slips of this design are the same as standard "UPS" Heads to provide all the important "UPS" advantages outlined at left. However, the flange is attached to the main body by means of a square thread so that it can be readily removed when drilling operations are completed.

During drilling, the flange is installed on the Head to provide means for attaching standard pressure control. A unique packing arrangement—having important advantages over the conventional ring-groove design—prevents leakage between the flanges and is so placed that the square thread is not exposed to casing pressure.

After drilling is completed, the pressure control equipment is removed and the flange is unscrewed from the Head—an operation simplified by the easy make-and-break properties of the square thread. The flange, ring bolts and packing can then be used repeatedly on other wells, thus effecting important economies on multiple installations.

Available in a complete range of sizes and designs, Type "UPS-DF" equipment is the latest in a long string of Baash-Ross Landing and Casing Head advancements. *Be sure to investigate the economies this equipment can make for you!*

BAASH-ROSS TYPE "X" HEADS Provide Vital Advantages for High-Pressure Installations.

CERTIFIED

Baash-Ross Landing, Casing and Tubing Heads are available through leading supply stores.

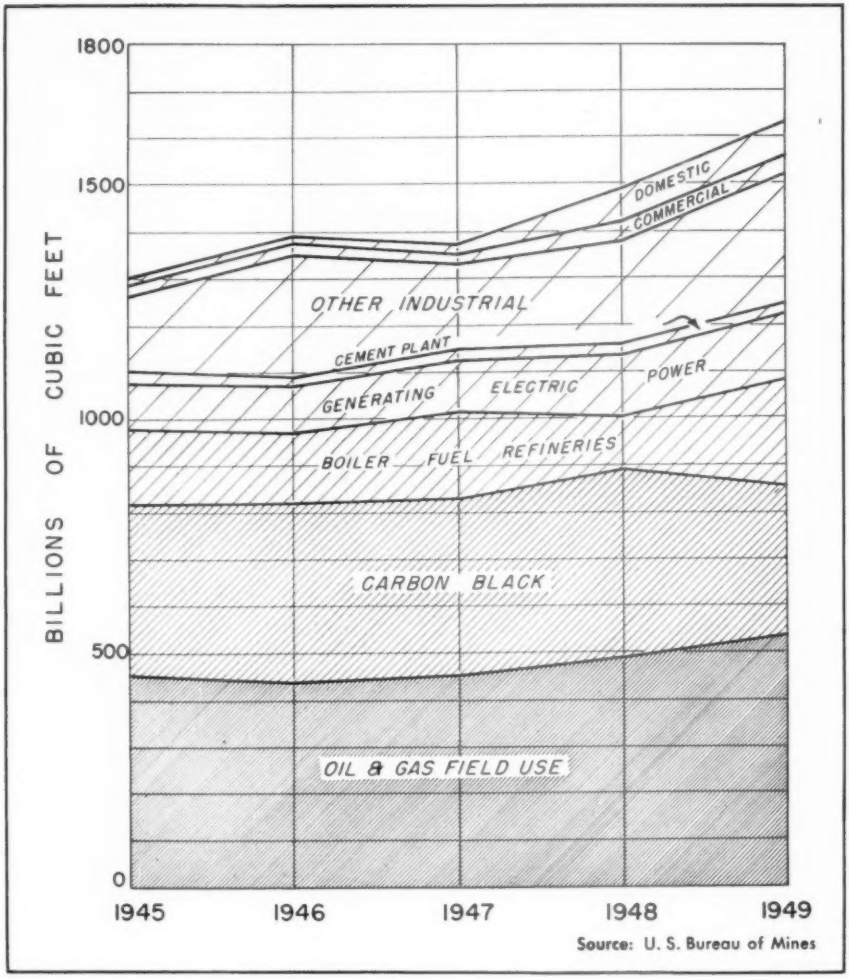
Developed several years ago to give new efficiencies on high-pressure wells, Type "X" equipment has been widely used on wells of all depths and pressures. It offers an unusual degree of simplicity, compactness and ready-adaptability to different installation requirements, and the heavy-duty pack-off provides a dependable seal against the highest well pressures. The pack-off is made in a separate unit that fits between flanges—a pressure-tight seal being formed around the casing by a double-element Packing Assembly tightened by stud bolts.

TYPE "X" ADVANTAGES INCLUDE . . . (1) No grooves or threads in the bowl of the Head—therefore nothing to become damaged or corroded during drilling operations, nothing to require maintenance or protection . . . (2) The one-piece Packing Assembly mounts between flanges for simple installation, maximum saving in space . . . (3) Unitized Slips assure uniform slip pressure, freedom from casing damage . . . (4) The Packing Assembly as well as the casing weld are so designed that the seal around the casing can be checked at any time during the life of the well, and if a leak is discovered can be readily packed-off with plastic material *without dismantling the Head or even breaking connections.*

Type "X" Heads are unusually adaptable to varying completion requirements—permit changing series-ratings and flange sizes in the Heads—and have many other unique features. They are available in a complete range of sizes, pressures and variations to meet every well requirement!

See pages 421 through 430 of your 1951 Composite Catalog for more data on Baash-Ross Landing and Casing Heads. Or write to your nearest Baash-Ross Sales Office.

HOW NATURAL GAS IS USED IN TEXAS



Source: U. S. Bureau of Mines

An excerpt from our booklet, "Texas—First in Natural Gas" . . . presented for your information by our Oil and Gas Division.

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AIME Honorary Membership Citation Given E. DeGolyer

E. DeGOLYER

AT the Annual Banquet of the AIME in New York City's Statler Hotel Feb. 20, a citation will be read commemorating the election of E. DeGolyer, of the firm of DeGolyer and MacNaughton in Dallas, to Honorary Membership in the AIME. The citation for this coveted award, held only by 20 living men, reads:

> "For distinguished service to the petroleum industry through his pioneering in the application of geophysical techniques to oil finding, and in recognition of the many contributions he has made to our understanding of the occurrence of petroleum and natural gas, and in grateful acknowledgment of his unselfish and patriotic service to his country, by his leadership, sound counsel and excellent judgment, both in time of peace and in the face of war, which has brought honor to himself and to the Institute."

The JOURNAL OF PETROLEUM TECHNOLOGY thought it fitting to ask several AIME members who have been close to E. DeGolyer to write brief appreciations of this man who has influenced petroleum engineering and geology so much. These appear below.

By A. Rodger Denison
Amerada Petroleum Corp., Tulsa, Okla.

E. DeGolyer — inquisitive, imaginative, versatile. He is as inquisitive in the "research" needed for proving that the Biblical character Job was the first petroleum geologist as that the silver mines of Laurium enabled Athens to dominate the ancient Greek world.

His imagination brought the classical earth instruments, the torsion balance and the seismograph, to oil exploration. His suggestion on visiting a laboratory for the study of core samples "put wheels under" the instruments and sent them to the field.

Geologist, business executive, author, editor, publisher, civic leader, college professor, raconteur, advisor to United States and foreign governments, thrice medalist, holder of numerous honorary degrees, citations from the oil industry and scientific societies. Such is the versatility of the man.

He is a man who never let executive duties interfere with his geological curiosity.

He is likewise a man who never let geological theory blind him to economic reality.

He is, in short, a man who can be equally enthusiastic over a fresh, new exploration concept as in initiating a new billion dollar corporation.

Who, more than he, typifies the judicious application of scientific principles to the art of oil exploration?

Who, more than he, typifies the American opportunity for individual initiative and enterprise?

Who, more than he, typifies the Horatio Alger saga?

The answer is no one.

By W. S. Morris
East Texas Salt Water Disposal Co., Kilgore, Tex.

It has been my privilege to know many of the outstanding engineers in the petroleum industry, but none has enjoyed the enviable reputation of E. DeGolyer, the oil man's "oil man." He is a recognized international authority of the petroleum engineering profession.

Dee reached the pinnacle because of many factors, prominent among which is his insatiable thirst for knowledge. His thinking is far ahead of where attention is generally focused. He is receptive to ideas; he has the vision to see things that need to be done; he has drive to put ideas into action; he is a seeker of the unknown and solves problems by the application of engineering, geological, and economic horse sense.

His faculty for evaluation has resulted in his surrounding himself with good men. To many young engineers, he has given a wealth of vision out of his own experience. He has taught them about economics, the value of money, the necessity of research, and last but not least, to think objectively. Many are leaders in the petroleum industry today, and others will be leaders in the future.

He has been responsible for many technical advances of the industry, including the mapping of subsurface formations by refraction and reflection seismic methods. For his outstanding work, he has been awarded medals by geologic and engineering societies — in fact, he has been referred to as the "maker of medals." Notwithstanding all the success that he has achieved and the honors that have been bestowed upon him, Dee found time to serve his country in the last World War in the Petroleum Administration for Defense. He also finds time to counsel and advise younger men in the petroleum industry to the end that he has won for himself a warm spot in the hearts of all who know him. To know him is to love him, and to name him is to praise.

By Wallace E. Pratt
Geologist, Retired, Carlsbad, N. M.

The characteristic which distinguishes E. DeGolyer is intelligence — practical, inquisitive, vivid intelligence. This talent has distinguished his entire professional career. No one who has spent as much as an hour in conversation with him can have failed to recognize the amazing quality of his mind — his animated, almost luminous mentality.

It is this quality of mind and the impression it made on those who encountered it, which carried DeGolyer, a boy just out of school, in a short span of years, from the position of field assistant on a U. S. Geological Survey party in Wyoming (DeGolyer himself maintains he was only the camp cook, employed for the summer), to that of chief geologist of the British-owned Mexican Eagle Oil Co., in Mexico, perhaps the largest crude oil producer on the North American continent at the time.

It is this same quality of mind which made DeGolyer, after a few years in Mexico, where he devoted his spare time to research among Spanish-language sources on the early history of the Southwest, the choice of the Board of Editors of Encyclopedia Britannica as the authority best qualified to write a biographical sketch of General Santa Anna for the 14th edition of that work.

Yet nowhere in DeGolyer's intellectual processes is there any trace of the indecision that has been described as "the pale cast of thought." His is eminently the psychology of the male animal — vigorous, almost belligerent. As an expert witness, in the verbal rough-and-tumble of a public hearing before a Congressional committee, he is at his best. His testimony is pithy and it carries conviction. It is courageous — he is in nowise restrained by the realization that his recommendations will not be universally approved by his colleagues in the petroleum industry.

Early in 1948, James V. Forrestal, then Secretary of Defense, discussed with me the current situation in the petroleum industry in relation to national defense. He was well informed. His views were clearly defined and positive. When I remarked these facts, he replied, in effect: "I am fortunate in that here in my official capacity I continue to enjoy the same advice on oil problems that I learned to rely on a long time ago in the business world. I mean DeGolyer. In my judgment his counsel in this field is the best the government can obtain. I have long been convinced that he is the most competent authority in the petroleum industry."

By Paul Weaver
Gulf Oil Corp., Houston, Tex.

That DeGolyer has been an outstanding administrator in petroleum companies is proved by his success with the Mexican Eagle, the Amerada, the Rycade, and in a consulting capacity. That he has been outstanding in the technical societies is also evident from the positions which he has held, especially in the AIME and the AAPG.

To the ones who have known him for many years these accomplishments have been an inspiration and a stimulus. A record such as his must be based on special contributions to the petroleum industry, two of which I consider outstanding:

First, his interest in the evolution of ideas and of technology. He has always been a serious student of the history of science and of engineering, and has known that from such studies valuable lessons can be learned. Many engineers do not think of our debt to the past and are likely to be subject to the poet's criticism . . . "Those who will not read history shall be condemned to repeat its mistakes."

The second important factor, it seems to me, is his recognition that new ideas and practices cannot be put to all of their uses without special organization for their rapid testing and widespread use under operating conditions. When he decided on a geophysical organization he immediately began contracting in order that the methods should be tested in diverse environments. He adopted the same viewpoint in regard to the examination of subsurface samples of reservoir rocks. Some engineers have a feeling that they themselves or their own organizations are adequate for the development of new techniques. If this viewpoint had prevailed we would not have the efficient service companies which are so important in the American petroleum realm. Although service companies operate now in many capacities, at the time that DeGolyer acted on this principle it was not a generally accepted one, and he can be considered to have pioneered this development of special technical services.

Paul R. Turnbull . . . 1952 Petroleum Branch Chairman

Early each October, Paul and Margaret Turnbull pack a few week-end clothing items into a bag, load up their car and head north from their attractive Corpus Christi, Tex., home.

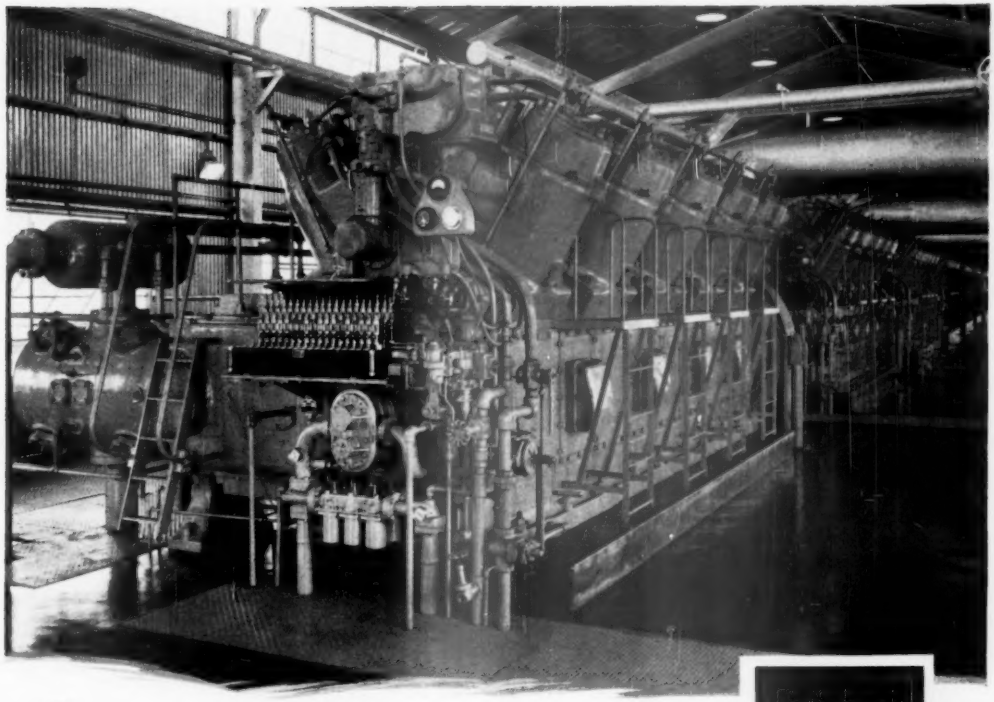
Their destination is Dallas, headquarters for the Petroleum Branch, AIME, office. Dallas is also the site of the Cotton Bowl, a huge shrine dedicated to football, where the University of Oklahoma and the University of Texas each year pit, on neutral ground so to speak, their finest athletes. The latter site, rather than the former, is the destination of the Turnbulls. Paul, an alumnus of OU (BS in petroleum engineering), is one of the university's most ardent football fans. Margaret, unfortunately for Paul during this particularly exciting period, is an alumnus of the University of Texas. The rivalry in the stands during this annual game sometimes exceeds that on the playing field.

After the annual meeting in New York this month, Paul Turnbull will have further reason to communicate frequently with Dallas. At the Petroleum Branch Banquet in the Statler Hotel, he will take over the chairmanship for 1952 of the Branch from R. W. French. Paul (see cover) comes from the spirited Southwest Texas Section, relatively young among the family of Branch sections. It was formed in 1947 with Paul being elected its first chairman. That same year he was the new section's delegate to the AIME Annual Meeting in New York. Five years later he returns as Branch Chairman.

In 1948 he served as a director of the section and in 1949 was vice-chairman of the Production Technology Committee (now Technology Committee) which is charged with the responsibility of arranging for the authorship of sufficient technical papers for the various Branch meetings. That same year, Paul acted for the chairman in arranging a program for the Mid-Continent Fall Meeting of the Branch in San Antonio, Tex. During 1951, he served as vice-chairman of the Branch.

After being graduated from the University of Oklahoma in 1929, Paul joined Humble Oil and Refining Co. He was affiliated with Humble for the next 19 years working in West Texas, East Texas and Southwest Texas areas. From August, 1946, to September, 1949, he was division petroleum engineer of Humble's Southwest Texas Division at Corpus Christi. In mid-1949 he became manager of the drilling and production departments of the La Gloria Corp. in Corpus Christi.

His career was interrupted during the war years when, in 1942, he entered the Air Corps as a second lieutenant, serving in the European theater of operations for 22 months. In September, 1945, he retired from active duty with the rank of major. ★ ★ ★



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TAKE a look at the compact, clean-cut line of engine-driven compressors shown here — seven Cooper-Bessemer 10-cylinder GMV's. Not so long ago the rating of these units would have totaled 7,000 horsepower. But with today's *supercharged* GMV's, it adds up to 9,450 horsepower. Thus, 7 GMV's are now doing the work of 10 older-type units . . . *with no increase in speed* and in only 7-unit space. Think what this saves in installation cost, piping, housing, maintenance, supervision and other expense items!

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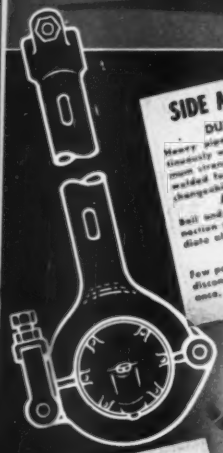

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Heavy pipe construction—continuously welded to give maximum strength and capacity. Jig welded for accuracy and interchangeability.

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Ball and socket crank pin construction giving automatic immediate alignment.

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Few parts—single bolt latch for disconnecting—smooth appearance.

LUFKIN GIVES YOU—the best in materials and design possible for our engineers to pack into each component part. Every part is made to be tough, so it will stand up under the toughest service—but easy to maintain. Note the features of these Lufkin assemblies which help to make Lufkin first in service, safety, dependability and efficiency.

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FABRICATION
Jig welded to insure interchangeability.

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Designed for rigidity with considerable reserve load carrying capacity.

MATERIAL
The samson posts are made from wide flange beam sections.

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Bronze bushed with large bearing area to carry heavy loads.

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Oil bath, dust proof construction with breather which allows moisture to escape. This eliminates oil contamination and costly repairs.

CRANK PIN FIT
The taper ground crank pin and the crank pin hole are checked with precision gages insuring a perfect fit and interchangeability.

BASES

MATERIAL
Bases are made from wide flange beam sections with stiffeners to give extra rigidity where the most weight is concentrated.

INSPECTION
Each base is template drilled and thoroughly inspected before it leaves the plant.

VARIETY
Bases are made to fit every type of prime mover and can be furnished with or without sub bases.

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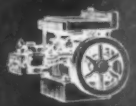

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Synthetic Liquid Fuels by Coal Hydrogenation

Reported by W. B. Davis
Mid-Continent Section

The manufacture of synthetic fuels by coal hydrogenation is uneconomic at the present time, Paul R. Schultz told members of the Mid-Continent Section last month. Manager of the economics department of Stanolind Oil and Gas Co., Schultz spoke after the regular monthly dinner meeting in Tulsa.

Schultz based his remarks on a comparison of two reports estimating costs of establishing and operating a coal hydrogenation plant at Rock Springs, Wyo. One of these reports, prepared by the National Petroleum Council at the request of the Secretary of the Interior, showed that gasoline produced at this hypothetical plant would cost about 40 cents per gal. A similar report issued by the U. S. Bureau of Mines indicated a cost of about 11 cents per gal.

Schultz said the USBM's estimate of costs was too low for several reasons: Investment cost was underestimated while the capacity was over-estimated; other capital charges, including housing, start-up expense, working capital, etc., were either underestimated or left out entirely; labor, raw material, and maintenance costs were too low; by-product credits were over-estimated; and insufficient return on capital was allowed.

The NPC committee work was undertaken in June of 1950. Subcommittees were organized to cover raw materials, process, engineering, and economics. Indicating the complexity of the problem and the thoroughness with which the project has been studied, 152 men served on or assisted the subcommittees; 115 outside companies were consulted; and the work cost about $300,000.

The accompanying tabulation summarizes the comparison between NPC and USBM estimates. While the USBM estimated that the plant at Rock Springs would handle 30,000 B/D, the NPC found that it would handle only 27,000 B/D. While the amounts of liquid fuels produced are about the same there is considerable difference in the by-product chemicals. The NPC made a thorough market study to determine plant realization on chemicals and found them much lower than the USBM prices.

The NPC study found the required plant investment much higher than the figure published by the USBM. It appears, Schultz said, that the USBM has either ignored some very necessary cost adjustments or else has made major revisions to the process, that are not mentioned in their latest report. There is also a very large difference in housing expenditure. The USBM contends that $5 million will be sufficient to assist in expanding established communities in the plant area. They say public agencies, such as FHA, should be encouraged to assist with the development of community housing. The NPC consulted some insurance companies and found that they would loan money on such housing only if someone of recognized financial standing assumed full risk for continued operation of the plant. The NPC found that the FHA would approve no loans to a project of this kind at the time of construction.

It may be noted that the difference between yearly operating costs, without depreciation, is about $19 million. As a typical example of why this large difference exists, the NPC estimates that 238 men per shift will be needed for direct operation of the plant. The USBM estimates that only 156 men per shift will be necessary.

PAUL R. SCHULTZ

Coal Hydrogenation Plant at Rock Springs, Wyo. Comparison of NPC and USBM Estimates

	NPC	USBM
Input coal, Tons/D	12,960	13,380
Output, B/D		
Motor gasoline	19,490	18,550
Liquefied petroleum gases	6,390	7,100
Chemicals	1,120	4,350
Total	27,000	30,000
Investment, millions of dollars		
Coal mines, plants, etc.	473	406
Housing and general community	60	5
Total	533	411

The difference in operating expense, depreciation and credit for by-products cause the NPC and USBM cost per gallon to differ by a factor of about 2; that is, if the USBM cost figures were applied to a financial setup identical to that assumed by the NPC, the USBM cost would be about 20 cents per gallon. However, because the USBM assumed that 60 per cent of the necessary capital could be borrowed and that an annual return of 6 per cent would be sufficient to attract the remaining 40 per cent equity capital, the estimated costs per gallon differ by a factor of about 4 instead of 2. A leading auditing firm has indicated that for a venture such as a synthetic liquid fuel project, an annual return, after income tax and depreciation, of 15 per cent of the total invested capital would be required to attract equity capital. This applies to all percentages of equity capital in the range of 80 to 90 per cent, as currently found in the petroleum and chemical industries; hence, it is felt that the USBM financial setup is totally unrealistic.

"When the time comes for commercial production of synthetic fuels, the petroleum industry will be ready. Until that time it would be a great waste of

Continued on Page 5, Section 2

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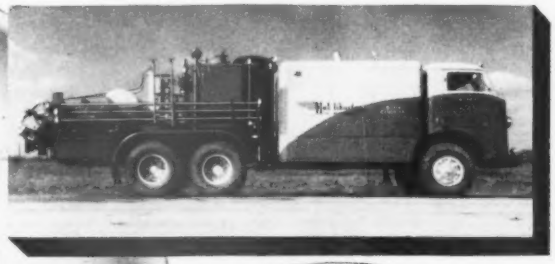

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Pressure Maintenance At the North Coles Levee Field

Reported by D. B. O'Neill
Pacific Junior Group

C. A. Davis, northern division engineer for Richfield Oil Corp., outlined the features and problems of pressure maintenance at the North Coles Levee Field in California's San Joaquin Valley last month at a meeting of the Junior Section of the Pacific Petroleum Chapter in Downey, Calif.

The North Coles Levee Field, located on the floor of the San Joaquin Valley in California, was discovered in January, 1938 and, like other oil fields such as Ten Section, Canal and Strand, seismic work played the major role in its discovery. As a tribute to the accuracy of this exploratory work, the discovery well was found to be within two locations of the apex of the pool. The structural extent of the field is about 3,200 acres; however, the productive boundaries have not yet been established in the east-west direction, although the north-south limits have been fixed by a number of dry holes and by several wells which penetrated thin sand sections before reaching the water table. The field is four miles long and one and three-quarters miles wide.

The original well, KCL-A 32-32, was completed in January, 1938, with an initial production of 3,000 B/D of 32° gravity oil, GOR 6,000 cu ft/bbl. Initial reservoir pressure was 4,000 psi, the bottom hole temperature was 220°F, the solution GOR was 650 cu ft/bbl and the formation volume factor was 1.39. The bubble point pressure was 2,550 psi, viscosity 0.5 cp, the average porosity 20 per cent, interstitial water 20 per cent and the average permeability about 125 md.

All of the producing measures of the North Coles Levee Field are members of the Stevens sand of Upper Miocene age, although they have been divided into the 21-1 zone, the Main Western (comprising the Upper and Lower Western) zone, the western 29 zone (which is in the northwest portion of the field) and a so-called Deep zone. The 21-1 zone is the highest productive zone stratigraphically. It pinches out or shales out at the top of the structure, although it is well developed on the flanks. The upper and lower western are pressure connected; however, there is a production, pressure or permeability barrier in the northwest portion of the pool which accounts for the classification of the Western 29 zone. To the east, the 21-1 zone merges with the Upper Western and the shale between them disappears. Data in this area indicate the sands become increasingly less permeable to the east.

Structural closure of the Main Western zone on the western nose of the field is about 1,300 acres with dips of 16° as compared to 6° on the flanks. An interesting feature of the North Coles Levee Field is the existence of a tilted water table which takes the shape of an inverted sauce dish. Such is not uncommon in other similar fields such as, for example, South Coles Levee, and may be a function of the variations in permeability and the lensing in and out of the sands. There is no evidence for a water drive, probably because of the low permeability on the flanks.

There are now 140 producing wells in the field. The primary spacing was one well to 40 acres, is now one to 20. Twenty-two wells remain to be drilled. The cost of drilling a well is estimated at about $125,000-$140,000 which is no more than it cost to drill a well in 1944, due largely to the improvement in drilling techniques.

The original drilling program called for cementing a 13⅜-in. surface string, and 8⅝-in. water string and a 6⅝-in. liner. Now the practice is to use 11¾-in. casing for the surface string, a 7-in. water string and a 5 or 5½-in. liner, or a 7-in. combination string is used without a liner. The latter method is the more common, especially since it enables the cementing of 5-in. or 5½-in. sleeves to eliminate gas entry as the gas cap moves down toward the oil-water contact, a natural result of the pressure maintenance operation. At one time, Richfield Oil Co. attempted to cement blank liners and gun perforate for production. This method, however, resulted in poor productivity of the sands and is no longer employed. An involved practice is now used in order to provide for sleeving off points of gas entry. An Amerada temperature bomb is employed in order to determine where to set blank sleeves. The bomb reveals clearly the temporature anomalies at the oil-gas contact, thus establishing the interval to be sleeved. The technique of sleeving is as follows: (1) Kill the well with oil base mud; (2) change to low-water loss clay base mud; (3) the interval to be sleeved is washed; (4) the cement is started down the hole; (5) oil base mud is used to prevent the cement from dropping below a certain prescribed point; (6) rubber plugs are used to control the movement of the cement and (7) the cement must be displaced in the annulus at a rate three to five times the rate at which the swabbing tool is removed up the hole.

The last item above is the most important operation in sleeving and is the "secret of their success" so to speak. After testing the sleeves to a differential pressure of 3,500 psi, cement is cleaned out so that only a 10-ft.± cement bridge is left. The sleeve is set with a packer on top of the cement bridge and cemented in place through tubing. The hole is then cleaned out, the oil base mud is displaced with oil, leaving the latter fluid behind the packer. The sleeves are 5 or 5½-in. Grade A soft steel which can be drilled out if necessary.

During the first four years of the field's life, conventional production practices were employed; *i.e.*, wells-

C. A. DAVIS

Officers of the Junior Section of the Pacific Petroleum Chapter for 1952 are as follows:

Donald B. O'Neill, Shell Oil Co., chairman.

Cedric Ferguson, Standard Oil Co. of California, program chairman.

Robert H. Burke, Southwest Exploration Co., secretary.

flowed naturally by means of the liquid expansion of the oil down to bubble point pressure. These practices also included shutting in of high GOR wells. During this time rapid pressure declines were, of course, encountered in the reservoir.

After the Main Western pool had been delineated by drilling of additional wells, thought was given to instituting a pressure maintenance program. After considerable study of successful applications of pressure maintenance in the Mid-Continent (specifically the Gulf Coast area), it was concluded that such a program would be economical at the North Coles Levee Field. The producing pressure was maintained for all wells at a point above solution pressure (*i.e.*, 2,550 psi) and this is felt to be one of the main contributing factors to the success of the project. The plant capacity has been enlarged twice since January, 1942, from its initial capacity of 3,600 HP and 31,000 Mcf/D to its present capacity of 8,640 HP and 73,000 Mcf/D. The plant currently handles 60,000 Mcf/D.

Significant illustrations of the project's success are that only six wells are on the pump (thus eliminating considerable capital outlay for the purchase of large pumping units), 10 are on a plunger lift; that the total lifting cost per barrel including taxes and insurance are only 35-40 cents and that during the past five years, the production rate has remained constant at 17,000 B/D oil.

Richfield has concluded to date (after nine years of pressure maintenance) that the ultimate recovery will be at least twice that which could have been anticipated from normal exploitation of the reservoir by natural depletion. The additional gas swept from the reservoir has more than paid for the project, especially in view of the substantial increase in the value of the gas per Mcf since the project was initiated. In addition, it was stressed that other factors aided materially in the success of the project. Some of these were: (1) Early gas injection before the reservoir pressure declined to the bubble point; (2) the strict production control which has been in effect — eliminating the formation of pressure sinks; (3) unitized control by one operator; (4) in spite of the low permeability (on the average), it has been permissible to use a wide range of production rates so as to permit each well to produce at its optimum rate; (5) the reservoir has a large closure with no faulting, and (6) there was available a large supply of make-up gas. ★ ★ ★

INCOMING CHAIRMAN GEORGE R. GRAY, right, took over the leadership of the Gulf Coast Section from A. W. Waddill, left, 1951 chairman, at the January meeting. Manager of the Gulf Coast Laboratory of Baroid Sales Division, National Lead Co., Gray will hold the reins as Gulf Coast members act as hosts for the 1952 Petroleum Branch Fall Meeting in Houston, Tex., next October.

SW Texas Section Wins Membership Drive

The Southwest Texas Section has been adjudged the winner of the 1951 Petroleum Branch membership drive conducted September through December. The section obtained 37 applications for the grades of member, associate member and junior member during the four-month drive. Its percentage increase over its 288 membership was 12.8.

CHESTER L. WHELESS, right, membership chairman of the Southwest Texas Section, receives the congratulations of Section Chairman Harry Vaughan after being selected to make the all-expense-paid trip to the Annual Meeting in New York.

A close runner-up was the East Texas Section which garnered 22 new applications for the above grades and a 12.2 per cent increase over its 180 membership roster. The contest rules stated that the section receiving the greatest percentage increase in membership during the drive would win the contest. The winning section was awarded an all-expense-paid trip for one of its members to the Annual Meeting in New York City held this month.

Chosen to receive the award was Chester L. Wheless of the La Gloria Corp. in Corpus Christi, Tex. He is Membership Chairman of the Southwest Texas Section. Wheless's award included air transportation to and from New York from his home, hotel expenses, an allowance for meals and complimentary registration at the meeting. He also received complimentary tickets to the Annual Banquet, Welcoming Luncheon and Stag Smoker.

A total of 192 new applications were received in all sections and chapters of the Branch. The number of new applications received by the various sections follows: Delta Section, 14; East Texas Section, 22; Gulf Coast Section, 21; Kansas Section, 7; Mid-Continent Section, 10; North Texas Section, 21; Oklahoma City Section, 10; Permian Basin Section, 14; Southwest Texas Section, 32; Illinois Basin Chapter, 5; Wyoming Petroleum Chapter, 5; and Pacific Petroleum Chapter, 26. ★ ★ ★

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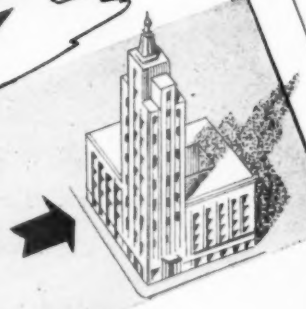

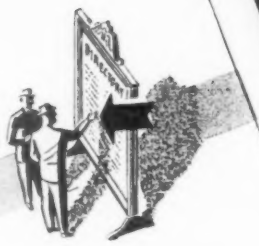

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A METHOD FOR PREDICTING THE TENDENCY OF OIL FIELD WATERS TO DEPOSIT CALCIUM SULFATE

HENRY A. STIFF, JR., MEMBER AIME, AND **LAWRENCE E. DAVIS**, THE ATLANTIC REFINING CO., DALLAS, TEX.

ABSTRACT

A graphic method was developed which can be used to predict the tendency of oil field waters to precipitate calcium sulfate under a variety of conditions. Application of this method is made to the prediction of sulfate scale formation in heater treaters, boilers, oil wells, cooling systems and water injection wells.

INTRODUCTION

A solution may be said to be in equilibrium with respect to a given salt when the concentration of that salt is equal to its solubility. If for any reason the concentration of the salt is increased or its solubility decreased, the equilibrium is upset and precipitation of the salt takes place. Thus, if the concentration of a salt in a particular solution is known and its solubility can be calculated for a given set of conditions, the tendency of this salt to form a precipitate under these conditions can be predicted. Based on these principles a method has been developed for determining the tendency of oil field waters to form calcium sulfate precipitates under various conditions.

THE SOLUBILITY DIAGRAM

Calcium sulfate precipitation most frequently occurs when two waters are mixed; one containing calcium ions, and the other sulfate ions. As one of these waters is added to the other a point may be reached where the concentration of calcium sulfate is greater than its solubility, thus causing the formation of a precipitate. The solubility diagram is a graphic device for determining the location of such points, thereby making possible a prediction of the tendency of such a system to deposit sulfate scale. A similar diagram can be used to solve many other problems involving the precipitation of calcium sulfate.

Fig. 1 shows a solubility diagram representing the mixing of two waters. Water "A" contains a high concentration of sodium, magnesium, and sulfate ions together with a small amount of calcium. Water "B" contains a high concentration of calcium ions together with sodium, magnesium and a small amount of sulfate ions. The percentage mixture of these waters is plotted along the abscissa of a system of rectangular coordi-

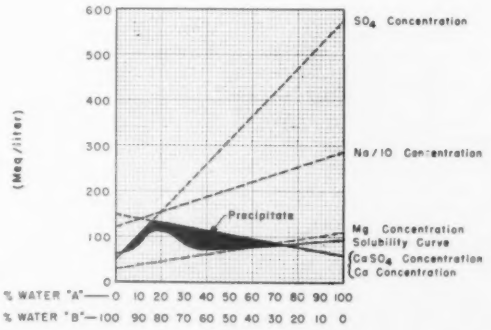

FIG. 1 — SOLUBILITY DIAGRAM, CALCIUM SULFATE DEPOSIT FORMATION WHEN TWO WATERS ARE MIXED.

Manuscript received in the office of the Petroleum Branch June 28, 1951. Paper presented at the Fall Meeting of the Petroleum Branch in Oklahoma City, Okla., Oct. 3-5, 1951.

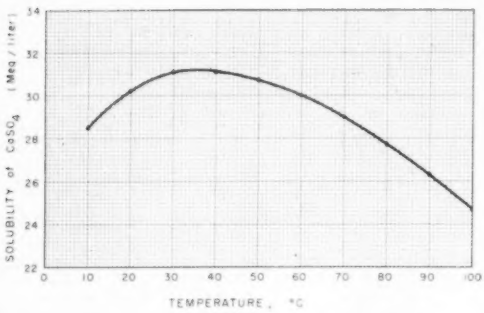

FIG. 2 — SOLUBILITY OF CALCIUM SULFATE IN DISTILLED WATER AT VARIOUS TEMPERATURES (S_1).

nates, while the concentration of the individual ions (in meq. per liter) is shown on the ordinate. The analysis of water "A" is plotted at 100 per cent "A," while the analysis of "B" appears at 100 per cent "B." Straight lines connecting the points representing the same ion then give the concentration of this ion at any percentage mixture of the two waters. The concentration of calcium sulfate is limited up to a certain point by the amount of calcium present. Above this point the amount of sulfate becomes the limiting factor. Thus the concentration of calcium sulfate at any percentage mixture of the two waters can be determined.

The solubility of calcium sulfate at any point is determined from the equation

$$S = S_1 \times F_1 \times F_2 \times F_3$$

where:

S = The solubility of calcium sulfate under a given set of conditions.

S_1 = The solubility of calcium sulfate in distilled water at the temperature T, as shown in Fig. 2.

F_1 = The common ion factor, or the solubility of calcium sulfate in the presence of an excess of calcium or sulfate ion, as given in Fig. 3.

F_2 = The sodium ion factor, or the solubility of calcium sulfate in the presence of sodium ion, as shown in Fig. 4.

F_3 = The magnesium ion factor, or the solubility of calcium sulfate in the presence of magnesium ion, as in Fig. 5.

When the solubility of calcium sulfate at several points has been calculated, a solubility curve can be plotted as shown in Fig. 1. Then at the percentage mixtures of the two waters where the concentration exceeds the solubility, as shown in the shaded areas, precipitation of calcium sulfate will take place.

Precipitation of calcium sulfate can be caused by evaporation of the solvent to the point where the concentration of the salt exceeds its solubility. This case can be treated by the diagram shown in Fig. 6. The ionic content of the water under consideration is plotted along the ordinate at one extreme of the abscissa. The abscissa itself is then marked off in percentage volume concentration of the solvent. At some convenient percentage volume concentration (50 per cent or 75 per cent) the ionic content is recalculated and plotted. Straight lines connecting the points representing the individual ions are then drawn as before. The calcium sulfate concentration and solubility curves can then be plotted and the areas of precipitation shaded.

Decreases in solubility brought about by changes in temperature can be handled by the solubility diagram shown in Fig. 7. Temperature is laid off along the abscissa. Ionic concentrations are plotted on the ordinates intersecting at the extremes of temperature being studied. The points representing the same ions are connected as before, the concentration and solubility curves drawn, and the areas of precipitation shaded.

EXPERIMENTAL PROCEDURE

The evolution of the calcium sulfate solubility formula was based upon a series of preliminary experiments which led to the conclusion that the solubility of calcium sulfate in oil field brines in the *pH* range from 6.0 to 8.0 can be closely approximated by consideration of the four factors shown; and further that these factors seem to function independently of each other. Data from which the graphs were originally plotted were obtained from the International Critical Tables.[1] From this data several series of solubility diagrams were pre-

[1]References given at end of paper.

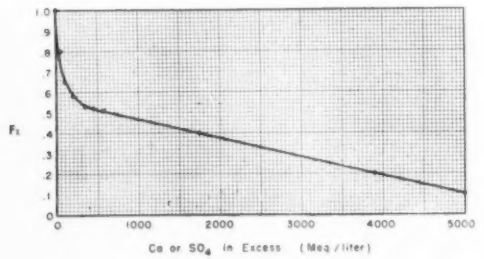

FIG. 3 — THE COMMON ION FACTOR, OR THE SOLUBILITY OF CALCIUM SULFATE IN THE PRESENCE OF AN EXCESS OF CALCIUM OR SULFATE ION.

$$F_1 = \frac{\text{Solubility of } CaSO_4 \text{ in presence of common ion}}{\text{Solubility of } CaSO_4 \text{ in distilled water}}$$

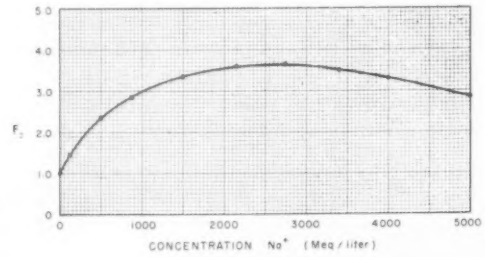

FIG. 4 — THE SODIUM ION FACTOR, OR THE SOLUBILITY OF CALCIUM SULFATE IN THE PRESENCE OF SODIUM ION.

$$F_2 = \frac{\text{Solubility of } CaSO_4 \text{ in presence of } Na+}{\text{Solubility of } CaSO_4 \text{ in distilled water}}$$

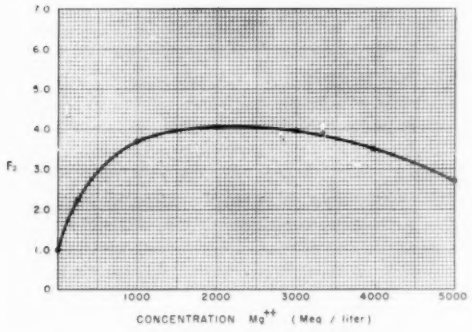

FIG. 5 — THE MAGNESIUM ION FACTOR, OR THE SOLUBILITY OF CALCIUM SULFATE IN THE PRESENCE OF MAGNESIUM ION.

$$F_2 = \frac{\text{Solubility of } CaSO_4 \text{ in presence of } Mg++}{\text{Solubility of } CaSO_4 \text{ in distilled water}}$$

pared similar to Fig. 1, in which one water contained calcium ion and the other sulfate. One of the other ions (sodium, magnesium and either calcium or sulfate) was made to vary in each series while the rest were held constant. Actual samples of the waters represented were then made up and mixed in various proportions. After equilibrium had been reached at a given temperature, the precipitated calcium sulfate was filtered off, ignited and weighed. On the basis of these data a new solubility curve was plotted and the curve for the corresponding factor corrected. The final curves were verified by mixing both prepared solutions and actual oil field waters. Data from these experiments also confirmed our conclusions that the factors affecting the solubility of calcium sulfate are mutually independent.

APPLICATION

The solubility diagram allows a prediction of the tendency of a water to form deposits of calcium sulfate under a given set of conditions. A few applications of this system are shown:

Scale Deposits in Heater Treaters, Boilers, Etc.

Calcium sulfate scale may be deposited in heater treaters, boilers, etc., because the increase in temperature brings about a decrease in the solubility of the salt. The tendency of a particular water to deposit this type of scale can be shown by a solubility diagram such as is given in Fig. 7. The intersection of the solubility and the concentration curves indicates the point at which calcium sulfate will begin to precipitate.

Scale Formation Due to Casing Leaks

If the analyses of the formation water and that of the strata from which the extraneous water is coming are available, a solubility diagram of the type shown in Fig. 1 can be constructed to show scaling tendencies. Conversely, the formation of calcium sulfate scale in excessive amounts in a well may indicate a casing leak, provided such scale can be shown to form as the result of the mixture of the formation water with water from an extraneous source.

Recirculating Cooling Water Systems

In some cases it may become necessary to use water containing considerable amounts of dissolved salts for cooling purposes in recirculating systems. In one such system water flows through heat exchange equipment where it is raised to a certain temperature. It is then passed through a spray pond or cooling tower in order to dissipate the heat. This water in passing through the tower is concentrated to a certain extent due to evaporation. By the use of a solubility diagram of the type shown in Fig. 6 the concentration at which calcium sulfate precipitates out can be calculated.

In the construction of such a diagram it should be remembered that the calculations are made at the temperature of the heat exchanger, rather than at the temperature of the spray pond.

Water Injection

Water injection problems are handled by diagrams similar to that shown in Fig. 1. In this case the graph may be considered as a cross section of the formation itself. Water "B" is being injected into a formation containing water "A." Along the length of the capillaries various percentage mixtures of the two waters will occur. If a deposit forms in any of these mixtures there will be considerable danger of plugging the capillaries with subsequent decrease in the permeability of the formation. Thus the solubility diagram can be used to forecast any tendency of two waters to form precipitates at any percentage mixture.

CONCLUSIONS

A method is presented by which the tendency of an oil field water to form calcium sulfate scale can be predicted from its analysis. Several applications of the method to the solution of typical production problems are given.

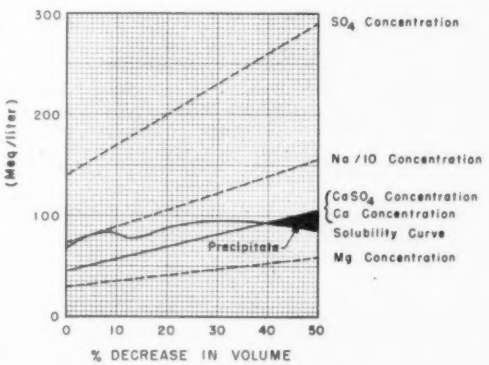

FIG. 6 — SOLUBILITY DIAGRAM, CALCIUM SULFATE DEPOSIT FORMATION WHEN SOLUTION IS CONCENTRATED.

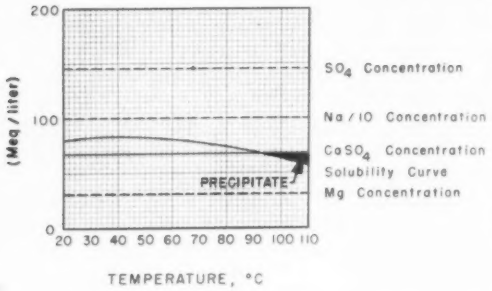

FIG. 7 — SOLUBILITY DIAGRAM, CALCIUM SULFATE DEPOSIT FORMATION WITH CHANGE IN TEMPERATURE.

ACKNOWLEDGMENTS

The authors wish to thank The Atlantic Refining Co. for permission to publish this paper, and to acknowledge the valuable assistance and cooperation of the staff of the Chemical Engineering Group of this organization. Illustrations were prepared by Gene Nigh.

REFERENCES

1. International Critical Tables, 1st Edition, Vol. IV, pp. 287-290.

DISCUSSION

By J. D. Sudbury, Continental Oil Co., Ponca City, Okla.

The authors are to be congratulated on their presentation of this timely paper. Its greatest importance lies in the prediction of the chemical compatibility of a water being injected into a formation containing a different water. Such systems include water injection systems for water flood projects and for disposal.

The prediction tool as described is purely mechanical and is quite simple to use, provided reliable analyses of the waters in question are available. Proof that the various factors affecting the solubility of calcium sulfate are mutually independent is very significant. This allows the determination of the various factors individually in the laboratory as they have done for the common ion effect, sodium effect, and magnesium effect.

By determining curves for only these three factors, it is feared that the authors have oversimplified the complex nature of many oil field brines. For example, strontium, barium, potassium, and lithium have also been found in most of the waters which we have analyzed. Strontium has been found in quantities as high as 2,200 ppm, barium up to 500 ppm, potassium up to 1,400 ppm, and lithium up to 100 ppm. In many cases, the strontium and barium contents are about as great as the magnesium content of the water. The solubilities of barium sulfate and strontium sulfate are 1/500,000 and 1/200 that of calcium sulfate. Thus, in many cases where concentrations of barium and strontium are appreciable, we would expect to get precipitation of their sulfates before getting any calcium sulfate deposition. Cases have been found where the deposition products are largely salts of barium or strontium. Even if they are not present in sufficient concentration to be precipitated ahead of calcium sulfate, factors should be determined for all of these ions in the same manner as was done for the sodium and magnesium. To illustrate the importance of this: the factor for 2,200 ppm strontium (49 meq per liter) is 1.35, and the factor for 1,400 ppm potassium (34 meq per liter) is 1.15; neglecting these factors would result in errors of 26 and 13 per cent in a calculated calcium sulfate solubility. These calculations assume that strontium follows the curve for magnesium (Fig. 5) and potassium follows the curve for sodium (Fig. 4).

Another factor which should be determined is the effect of *pH* on the solubility of the calcium sulfate. The solubility of calcium sulfate increases considerably with a decrease in *pH*. This effect is especially pronounced at temperatures near the boiling point of water. The *pH*'s of oil field brines have been found to vary in the range from three to nine. The presence of acid gases and organic fatty acids especially affect the *pH*.

It should be pointed out that the correction curves for sodium and magnesium were determined at one temperature and can be accurately used only at this temperature unless it is proved that the temperature effect is negligible. The only readily available calcium sulfate solubility data at various temperatures are for hydrochloric acid, ammonium sulfate, and sucrose. However, for these three the correction factor curves vary markedly with temperature.

Since the work of the authors showed all the factors affecting solubility to be mutually independent, it should be relatively simple to extend this paper by determining these additional correction factors. This would greatly broaden the applicability of their prediction method.

We have had considerably more trouble due to the deposition of calcium carbonate than of calcium sulfate. For this reason, I would like to ask the authors if they plan to extend this method to a study of the solubility of calcium carbonate? More specifically, have they determined whether or not the various factors affecting the solubility of calcium carbonate are mutually independent as was the case for calcium sulfate?

AUTHORS' REPLY TO MR. SUDBURY

The authors wish to thank the reviewer for his interesting and comprehensive discussion of this paper. We have, of course, given a great deal of thought to the matter of simplification and we agree that there are probably cases where our approach may be oversimplified.

The object of this study was to devise a workable technique for predicting the formation of calcium sulfate scale. Our most difficult problem was to determine the extent to which we could simplify the method. If too many factors are required, the solution of a problem would be too complex for practical use. If too few factors are taken into account accuracy would be sacrificed. We believe we have reached a satisfactory compromise. In the majority of cases the method will give good results. In some instances, however, the factors pointed out by Sudbury should, no doubt, be given more consideration.

Our studies were limited to brines within the *pH* range of from 6.0 to 8.0. We are sorry that this fact was inadvertently omitted from the preprint furnished the reviewer.

The authors are happy to announce that they also have a method for predicting the formation of calcium carbonate scale. We expect this paper to be available in the near future.

★ ★ ★

EFFICIENCY OF GAS DISPLACEMENT FROM POROUS MEDIA BY LIQUID FLOODING

T. M. GEFFEN, JUNIOR MEMBER AIME, D. R. PARRISH, G. W. HAYNES, MEMBER AIME, AND R. A. MORSE, JUNIOR MEMBER AIME, STANOLIND OIL AND GAS CO., TULSA, OKLA.

ABSTRACT

Flow tests on small core plugs have indicated that a large amount of gas is trapped and not recovered by water flooding a gas sand. Instead of 1 to 15 per cent pore space, as is usually assumed, the residual gas saturation is 15 to 50 per cent pore space, and is thus of the same magnitude as residual oil after water flooding oil sands.

A thorough investigation was made to ascertain that large amounts of residual gas actually remain in reservoirs after a water flood and that this condition is not merely a laboratory phenomenon. In field experiments, the amount of gas left in a watered-out gas sand was measured by use of a pressure core barrel and the residual gas saturation of two watered-out gas sands was determined by electric log evaluation. In the laboratory, an investigation was made of factors that could possibly cause the value of residual gas saturation as measured on small core plugs to differ from that in the reservoir, and the effect of these factors on the amount of residual gas saturation was studied. The factors studied include flooding rate, static pressure, temperature, sample size and saturation conditions before flooding. All evidence established that a relatively high gas saturation is trapped in water flooded gas sands and that this residual gas saturation can be measured in the laboratory by tests on small core plugs.

INTRODUCTION

There has been general agreement among engineers that very high recovery of gas could be obtained from natural reservoirs by water displacement. Gas recoveries of 80 to 95 per cent of the original gas in place have become the normal expectation in water drive fields. The assumption of high recovery has been based on:

1. low density and viscosity of gas compared with water;
2. the erroneous assumption that the flow relationships in a gas-liquid system where gas is the displaced phase will be the same as when it is the displacing phase.

It has long been recognized that gas can flow at very low gas saturations (in the range of 1 to 15 per cent pore space) in systems where liquid is being displaced by gas. By assuming the reversibility of this process, the conclusion was reached that the residual gas saturation following water flooding of a gas reservoir would be the same (1 to 15 per cent) as that at which gas first flowed continuously as a displacing phase. Recent laboratory relative permeability studies[1,2,3] have demonstrated that the flow characteristics are very different in gas-liquid systems, depending on whether gas is displacing or being displaced by, a liquid. Also, it has been shown that there is no difference between the flow characteristics of oil and water or gas and water in water wet porous rocks. The residual gas saturation that can be expected following water flooding of a gas reservoir then would be in the same range as the residual oil saturation normally expected after water flooding an oil reservoir, *i.e.*, in the range of 15 to 50 per cent pore space, depending on the rock characteristics.

Obviously, such a difference in residual gas saturation means very important differences in recoverable gas reserves from water drive reservoirs. For example, if the original gas saturation in a field were 70 per cent, and the residual gas following flooding were 35 per cent, only half of the gas in place could be recovered by complete water drive, compared to the previously expected 80 to 95 per cent. This is a situation in which complete pressure maintenance could result in very greatly reduced recovery, since straight pressure depletion recoveries from gas reservoirs can approach 80 to 90 per cent. Such a change in thinking must be based on more complete information than a series of small core tests. Hence the work reported herein was undertaken with the objective of determining whether or not residual gas saturations indicated from small core relative permeability tests at atmospheric pressure and room temperature are representative of the residual gas saturations which could be expected after water flood of natural reservoirs. A study was made both through laboratory and fields tests to determine any differences in residual saturation which might be occasioned by differences in pressure, temperature, rate of flooding, and original saturation conditions.

Four separate types of laboratory experiments and two field measurements were made in this investigation. The apparatus and testing methods of each will be discussed individually.

LABORATORY EXPERIMENTS, APPARATUS AND PROCEDURE

Relative Permeability Tests

Steady state flow experiments were conducted using the Penn State type apparatus. The equipment used has been described in a previous publication.[1] "Irreducible" water saturation was established in the core by imposing a capillary pressure of 45 psi before simultaneous flow of air and water

[1]References given at end of paper.

Manuscript received in the office of the Petroleum Branch Sept. 18, 1951. Paper presented at the Fall Meeting of the Petroleum Branch in Oklahoma City, Okla., Oct. 3-5, 1951.

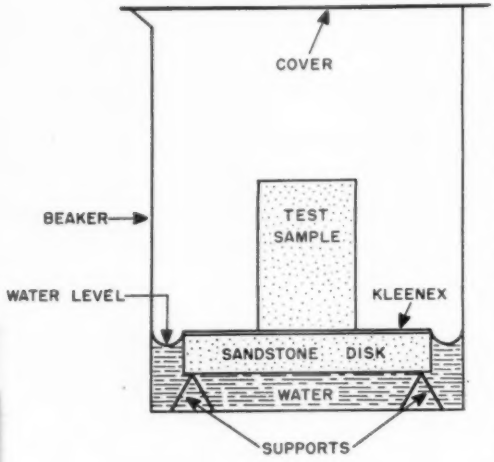

FIG. 1 — SCHEMATIC DIAGRAM OF WATER IMBIBITION TEST.

was started. The air and water were injected so that each succeeding equilibrium run had a higher water/gas ratio. Saturations were determined by electrical conductivity and gravimetric measurements.

Gas Displacement by Water in One-Foot Cores

Nellie Bly sandstone cores were used in this study. Cylindrical cores one and one-half in. in diameter and approximately one ft long were cut parallel to the bedding planes. Copper wire rings were placed at intervals along the length of the core and brass screen wires were placed against each end of the cores. Cores used in tests conducted at room temperature were encased in Lucite plastic sheaths, whereas those used for tests at 250°F were sealed in either phenol formaldehyde plastic or 3-M rubber sealing compound.

The cores were completely saturated with water, and then gas was injected into each end alternately to remove all but a near "irreducible" water saturation. After this, a desired gas pressure was established under a suitable back pressure and the cores were placed in a vertical position in a constant temperature bath. Flood water was supplied to the bottom of the cores in two ways. In those tests which were conducted at atmospheric pressure, water was injected at constant rates utilizing positive displacement pumps. In other tests, in which the gas pressure was 5,000 psi, a leveling bottle supplied the flood water under a head of a few inches of water.

Electrical conductivity measurements were made during the flooding operations. These values were converted to water saturations by means of an appropriate calibration curve. After flood-out, several pore volumes of water were passed through the cores.

Water Flood of a Simulated Gas Reservoir

A 16-ft column of Torpedo sandstone was made by butting together two cores which were cut parallel to the bedding planes. Bronze screen wire was placed across both ends of the two-in. diameter column and copper ring electrodes placed at two-in. intervals along its length. This entire assembly was sealed in a Lucite plastic sheath.

The core column was placed vertically in a constant temperature (80°F) cabinet. The core was completely saturated with brine and then allowed to drain to capillary equilibrium, at which time only the lower one-half foot remained fully water saturated. Above this, the water saturation covered the range from 100 to 30 per cent pore space.

After water drainage stopped, the top of the core was pressured with 96 psig nitrogen pressure and water injection was started. A pump was used to inject water into the bottom of the core at constant rates. Several injection rates were used until flood-out. After flood-out, testing continued with alternate periods during which water was injected and periods during which no water was supplied to the core.

Gas Displacement from Dry Core Plugs By Water Imbibition

Cleaned dry core plugs of the type usually used for core analysis were placed so that one end contacted a source of water, as shown in Fig. 1. Weight measurements were made at time intervals as the core imbibed water. Residual gas saturation was determined as the break in the curve of average water saturation *vs* the imbibition time.

FIELD EXPERIMENTS, APPARATUS AND PROCEDURE

Physical Measurement of Gas Saturation in a Watered-Out Gas Sand

The Carter Oil Co.'s pressure core barrel was used in measuring the gas saturation in cores cut from a watered-out gas sand. Operation and design features of the pressure core barrel have been adequately described in other publications.[4,5]

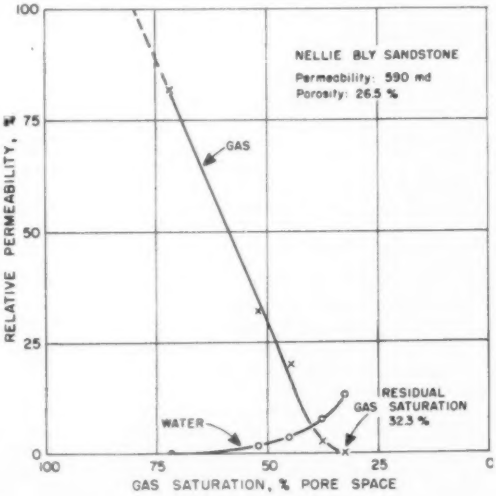

FIG. 2 — RELATIVE PERMEABILITY FOR DISPLACEMENT OF GAS BY WATER IN NELLIE BLY SANDSTONE.

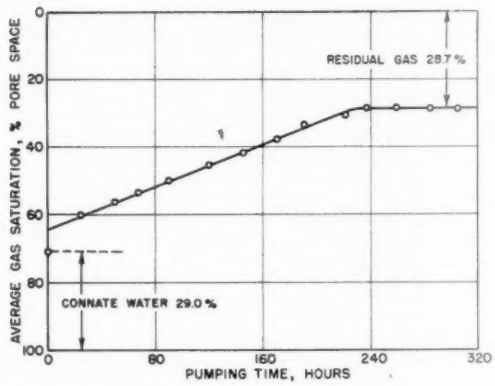

FIG. 3 — SATURATION HISTORY OF SLOW FLOOD (THEORETICAL RATE OF WATER RISE OF APPROXIMATELY ONE IN. PER DAY), NELLIE BLY SANDSTONE.

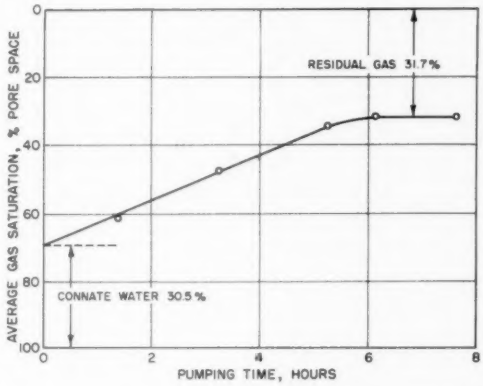

FIG. 4 — SATURATION HISTORY OF FAST FLOOD (THEORETICAL RATE OF WATER RISE OF APPROXIMATELY 54 IN. PER DAY), NELLIE BLY SANDSTONE.

The tool affords a means of coring subsurface strata and retrieving the cores at the surface under the same pressure that existed in the ground. Facilities are provided for making physical measurements on the core and the fluids it contains.

The entire section of the 4,500-ft gas sand of the West Beaumont Field, Tex., was cored with the pressure core barrel in four- and five-ft intervals. After pulling each core, all necessary measurements on the contents of the barrel were made. In addition to the physical measurement of gas saturation of the recovered cores, electrical logs were run and the gas saturation of the cored section calculated using the usual methods.[5] The residual gas saturation of a partially watered-out reservoir, Siphonina Davisi sand, Lakeside Field, Louisiana, was calculated using electric log data.

Results of each of the four laboratory tests and the two field studies are discussed separately below:

RESULTS AND DISCUSSION OF LABORATORY STUDIES

Relative Permeability Tests

The flow sequence in gas-water relative permeability tests on small core plugs simulates conditions of saturation changes that occur in gas sands that are undergoing a water flood. Provided there are no effects present in reservoirs which are not present in laboratory tests, the value of residual gas should be the same for a specific piece of rock regardless of its location. Residual gas referred to herein is the saturation at which gas ceases to be recoverable by water displacement.

Gas-water steady state relative permeability characteristics for a sample of the Nellie Bly sand-stone are given in Fig. 2. Maximum water saturation attained on this core plug was 67.7 per cent at flood out. This is equivalent to a residual gas saturation of 32.3 per cent pore space and will be compared to results of other laboratory flood tests conducted under simulated reservoir conditions.

Gas Displacement by Water in a One-Foot Core

The purpose of these tests was to evaluate the effect on residual gas saturation of: (a) rate of water advance, (b) static pressure, and (c) temperature.

A summary of results of the flood tests and relative permeability test on a small core plug is given in Table I. Agreement between all tests on order of magnitude of residual gas saturation after water flooding is good considering that several different cores of the same porous material were used in the studies. There is a small apparent effect of rate from a comparison of results of tests conducted on the same core with all conditions being the same except rate. This will be discussed further under a more thorough evaluation of each factor studied.

Effect of Rate of Water Advance

The histories of the two floods in which the rates of water advance were 1 and 54 in. per day are shown in Figs. 3 and 4, respectively. In both floods, a constant rate of average saturation change occurred until flood-out, then no change occurred with continued water injection.

The same core was used in these tests, yet the lower flooding rate resulted in a three per cent pore space lower residual gas saturation. This difference can partly, but not entirely, be attributed to experimental accuracy. It is recognized that

Table I — Vertical Flooding of Gas by Water
Nellie Bly Sandstone
Summary of Results

Rate of Water Advance In. Per Day Avg. (Approximate)	Pressure Static psig	Temp. °F	Residual Gas Saturation Per Cent Pore Space
100*	Atmospheric	80	32.3
1	Atmospheric	80	28.7
54	Atmospheric	80	31.7
4	5,000 psi	80	32.8
1	5,000 psi	250	33 - 36.5 (Three Cores)

*Reference run: relative permeability test on core plug.

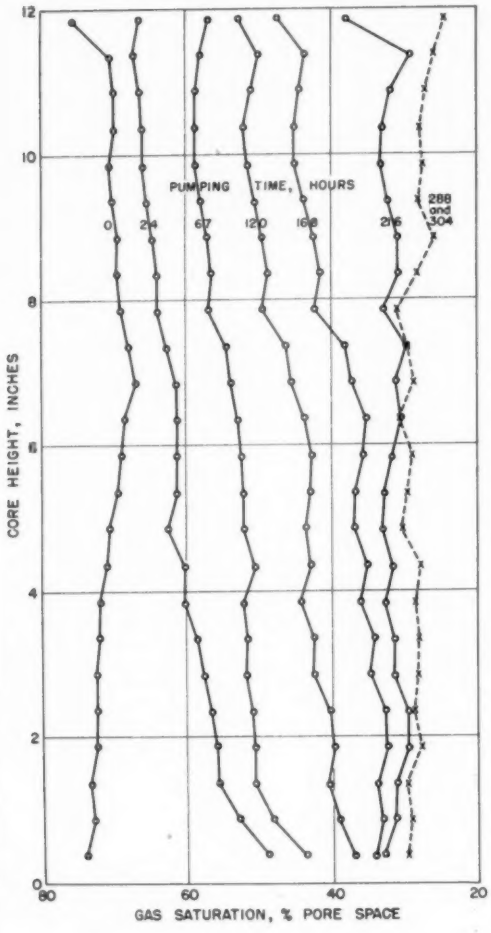

FIG. 5 — SATURATION PROFILES DURING SLOW FLOOD, NELLIE BLY SANDSTONE.

gas displacement by water does not result in a stable system. Trapped gas bubbles tend to leave the system by diffusion in order to establish thermodynamic equilibrium. A portion of the difference in residual gas saturation on the two tests in question can be considered a result of diffusion. The important question arises from this as to what the rate of diffusion would be in terms of saturation units at reservoir conditions of temperature and pressure. Gilliland[7] has developed from the kinetic theory of gases an expression for diffusivity which permits a reasonable evaluation of the problem. From this it was determined that for reservoir conditions of 250°F and 5,000 psi, the change in gas saturation by diffusion is 1/220 of the rate at 80°F and atmospheric pressure. Therefore, three per cent pore space gas that was removed from the one-ft core by diffusion during the laboratory tests at a rate of water advance of one ft in ten days would, in the reservoir, necessitate a rate of one ft in approximately six years. This rate is much less than usually occurs in producing reservoirs; therefore, it appears that gas diffusion could influence the results of laboratory tests at low pressures but is of little importance in the recovery of gas from reservoirs.

Following the fast rate flood, the core was left in contact with a source of water for 21 days, with no significant change in saturation taking place. This is attributed to an extremely low gas diffusion rate which resulted from the length of diffusion path. In this case, the average path was one-half the core length, or approximately six in. During the slow flood diffusion of gas was appreciably faster, since gas diffusion paths were small — in the order of sand grain diameters — in the saturation transition zone or flood front.

The data of the two floods show interesting results when analyzing the saturation distribution during the flooding periods. Figs. 5 and 6 show saturation profiles during the slow and fast floods, respectively. It is significant to note that in the slow flood the entire core saturation progressively changed while in the fast flood a typical flood front moved up the core. If only capillary (imbibition) forces are available to move water into the core, the profiles would assume a shape equivalent to the static capillary pressure curve of the system. In the slow flood the profile is elongated such that the total range of saturations between initial and flood-out conditions covers a length greater than the length of the core. In the fast flood the flood front is compressed to such a degree that the entire range of saturation exists within the core. Thus, the shapes of the saturation profiles of the two floods under discussion indicate that the low rate flood operated at a rate less than the imbibition rate and the other test at greater than imbibition rate.

It is concluded from the above discussion, that at reservoir conditions of temperature and pressure and reasonable flood rates, the effect of water flood rate on the efficiency of gas displacement is negligible.

Effects of Static Pressure

Flood history of an experiment in which methane at 5,000 psi static pressure was displaced by water is shown in Fig. 7. The driving force on the water in this experiment was capillary suction plus a few inches of water head. This produced a declining rate of water advance in the core. At flood-out the average residual gas saturation was 32.8 per cent pore space and was not changed by flowing enough water to replace the water in the core more than three times.

As in the preceding floods, the temperature of this test was maintined at 80°F. The value of residual gas saturation measured under pressure conditions of this test agree with those measured at atmospheric pressure.

Effects of Temperature and Pressure

Floods were performed at 5,000 psi static pressure and 250°F to simulate high pressure gas reservoir conditions. Recent research[5] has indicated that in certain systems a wettability change takes place at these conditions. Such an occurrence could change the displacement efficiency of gas by water from that at lower temperatures and pressures. Although the cited work investigated a system in which the solid phase was steel and not rock material, it was thought advisable to investigate the possibility of wettability changes in rocks at high temperatures and pressures.

Three separate Nellie Bly cores were flooded starting with approximately 27 per cent connate water. Flood histories for these tests are shown in Fig. 8. Residual gas saturations for

these were 34.0, 36.5, and 33.0 per cent pore space. Precision of measuring saturation was not as good in these tests as those conducted at 80°F because of difficulties in obtaining good electrical insulation at the high temperature. Regardless of this, the magnitude of residual gas saturation agrees with values measured at lower temperatures. The erratic flood histories of the three tests are a result of restricting the flow of water into the cores by regulating needle valves. It is significant to note that in each case after flood-out no additional gas was recovered regardless of the previous flood histories.

Saturation profiles at various times during the flood on core 2 are presented in Fig. 9. The driving force for the water in this case was capillary suction. The fact that the core imbibed water is sufficient to establish that the water was the wetting phase as it was in the floods at atmospheric conditions.

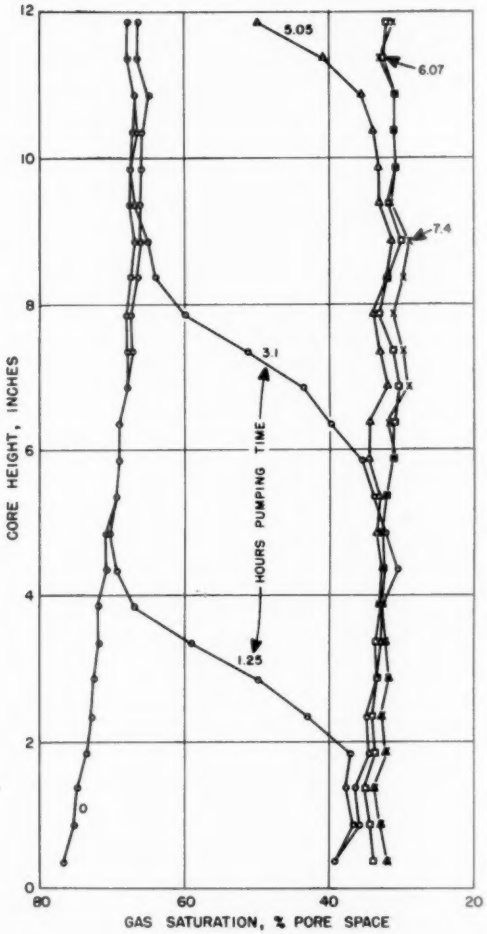

FIG. 6 — SATURATION PROFILES DURING FAST FLOOD, NELLIE BLY SANDSTONE.

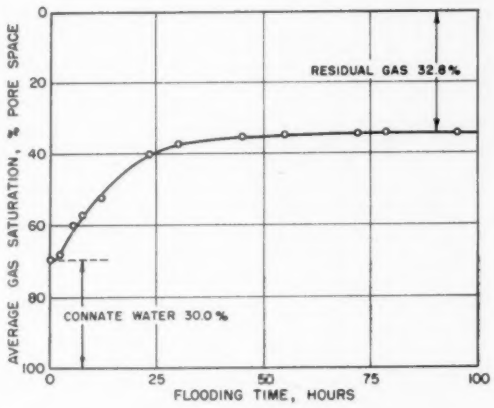

FIG. 7 — SATURATION HISTORY OF UPDIP WATER FLOOD WITH STATIC PRESSURE AT 5,000 PSI AND TEMPERATURE OF 80°F, NELLIE BLY SANDSTONE.

Water Flood on a Simulated Gas Reservoir

In a gas sand at the time of discovery, the vertical distribution of gas and water is in equilibrium with the capillary forces of the sand. Gas saturation starts from zero, low in the structure, and increases progressively upward. The flood tests already discussed were performed with the entire core at a high gas saturation before the flood. A flood experiment on a 16-ft column of Torpedo sandstone (an outcrop formation) was made with the gas saturation before the flood in equilibrium with the capillary forces to find out if this factor had an influence on the amount of residual gas remaining after a water flood. Results of this experiment are given in Fig. 10, in which the vertical distribution of gas in the core is shown at various times during the water flood.

Connate water saturation in the core before the flood ranged from 30 per cent in the uppermost portion, gradually increasing to 100 per cent pore space in the lower one-half ft. It should be noted that at about nine and one-half ft up from the bottom of the core the continuity of the connate water saturation profile is broken. This is at the location of the joint plane between the two cores in the column. The discontinuity means the cores were not in complete capillary contact and a saturation gradient due to end effect resulted when the core was drained. During the water flood the discontinuity had no disturbing effect on the saturations as a non-wetting fluid was displaced by a wetting fluid.

Flood-out occurred after 24 days of continuous water injection. The residual gas saturation remaining in the core varied in the same manner as the original gas saturation. A maximum residual gas saturation of 34 per cent pore space was measured in the uppermost portion of the column. Relative permeability tests on several Torpedo sandstone core plugs resulted in residual gas saturations covering the range of 34 to 37 per cent pore space when the connate water saturation before flooding was in the same range as in this portion of the long

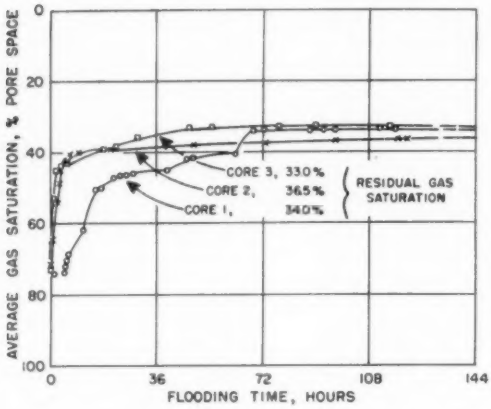

FIG. 8 — SATURATION HISTORIES OF THREE WATER FLOOD TESTS ON NELLIE BLY SANDSTONE CORES AT 5,000 PSI AND 250°F.

core column. Small core flow tests[1] have been shown to give the same variation in residual gas saturation as measured in the lower portions of the column when starting with comparable water saturation. After flood-out, an amount of water sufficient to flood out an additional 100 ft of sand was pumped through the core over a three-month period. During this time the gas saturation in the lower portion of the core gradually diminished. In the following two and one-half months period, during which no water was pumped into the system, the saturation at every position in the core remained stable. It is concluded that the small reduction in gas saturation in the lower portion of the core after flood-out was caused by solution effects. Considering the amount of water required to remove gas by solution, this method of gas recovery is not thought to be of practical importance in reservoirs.

In Fig. 10 the effect of rate of the displacement process can be seen. During the first 67 hours of the flood, the water was injected at a rate resulting in a water advance of approximately 20 in. per day. For the next 438 hours (67-505 hours total) the rate was reduced to approximately 10 in. per day. It can be seen that a twofold decrease in rate of water injection caused a twofold increase (from 3 to 6 ft) in the length of transition zone or flood front. This is the only apparent effect rate had on the displacement process; the magnitude of residual gas saturation was not affected.

Gas Displacement from Dry Core Plugs By Water Imbibition

In all preceding experiments described, the cores contained connate water before being water flooded. The question arose as to the amount of residual gas saturation that would remain after water flooding cores which were not initially subjected to the restored state technique. This involved water flooding a completely gas saturated core.

Capillary forces will cause spontaneous imbibition of water into porous materials that are wet by water in preference to air. Water thus imbibed into the core will displace air to zero air permeability in the same manner that it would if it were pumped into the core. This flooding-out of a core by water imbibition will progress until the vertical height flooded is equivalent to the displacement pressure of the rock sample.

Table II — Reproducibility of Determination of Residual Gas Saturation by Imbibition (1½-in. Diameter Samples)

Sandstone	Sample No.	Residual Gas Saturaton, % Pore Space Test 1	Test 2	Test 3
Torpedo	1*	34.5	—	—
Torpedo	2*	34.0	—	—
Torpedo	3*	34.2	33.6	34.3**
Torpedo	4*	35.1	—	—
Torpedo	5*	35.5	35.0	35.1**
	Avg.	34.7		
Nellie Bly		31.8	32.1	

*Cut from same block in order of number.
**Curved surface plastic coated.

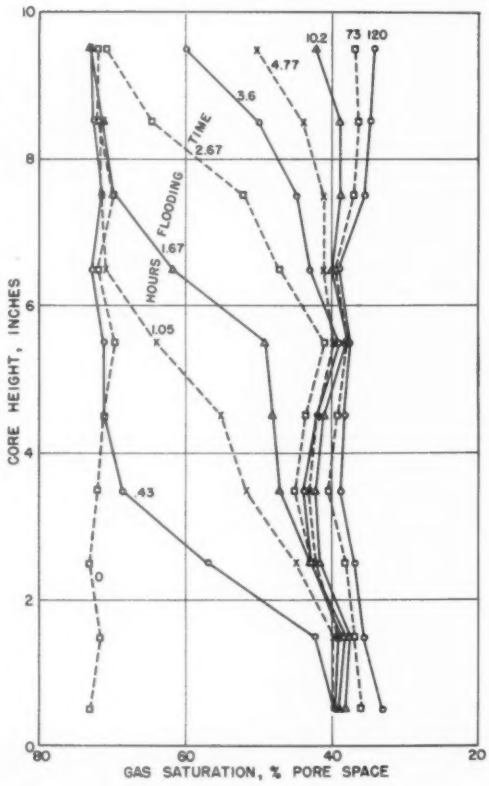

FIG. 9—SATURATION PROFILES DURING UPDIP WATER FLOOD AT 5,000 PSI AND 250°F, NELLIE BLY SANDSTONE (CORE NO. 2 OF FIG. 8).

Table III — Reproducibility of Residual Gas by Imbibition Tests (Different Size Samples)

Sandstone	Diameter, In.	Residual Gas Saturation % Pore Space Test 1	Test 2
Nellie Bly	1½	31.8	32.1
Nellie Bly	¾	31.8	—

Above this height only a partial flood will take place. Displacement pressures of the type porous materials of interest are greater than one in. of water; therefore, natural sand core plugs in the order of one in. in length can be completely flooded by water imbibition.

In these experiments water was imbibed from the lower face of the core with the remainder of the core in the atmosphere. It was found that completely submerging the cores had the disadvantage of mechanically trapping gas in the central portion of the core as water invaded from all directions, thus complicating interpretation of the data.

Cores used in these experiments were outcrop sandstones, reservoir cores, and synthetic porous materials. Typical data of a water imbibition test are shown in Fig. 11. Each set of data points is for the same core. The significant feature is the reproducibility of the residual gas saturation. Difference in measured values is in the order of precision that saturations can be determined by weighing the core. Before flood-out, and after the same amount of time, the amount of water imbibed in each test was different. This was entirely due to differences in the resistance offered by the supporting porous disks to the flow of water.

Repeat tests on the same cores were found to be reproducible within 0.6 per cent pore space. This is shown in Table II. The five Torpedo sandstone cores were cut from the same piece of rock and three tests were conducted on each of two cores. Sample diameter had no effect on the results as shown by data in Table III. Similar agreements of results were found between tests using core plugs whose curved surfaces were covered with an impervious plastic and tests before plastic was molded onto the core.

Table IV lists comparative results of imbibition tests on two cores performed with and without connate water saturation in the sample before imbibing water. The agreement is within acceptable limits. Table V gives comparative results of residual gas saturations measured on the same cores by flow experiments (relative permeability tests) and by water imbibition into dry cores. Again the agreement is acceptable, as the average of the five cores tested by the two methods differs only by one per cent pore space.

Oil was used for the imbibed fluid in other tests and results for cores in which both water and oil imbibition tests were conducted are shown in Table VI. The agreement is exceptionally good. These results indicate that over the range investigated, viscosity, density, and interfacial tension of the fluids

Table IV — Comparison of Residual Gas by Imbibition Tests on Cores When Dry and When Containing Connate Water

Sandstone	Residual Gas Saturation, % Pore Space Originally Containing Irreducible Water	Originally Dry
Nellie Bly	34.7	33.0
Nellie Bly	34.5	32.3

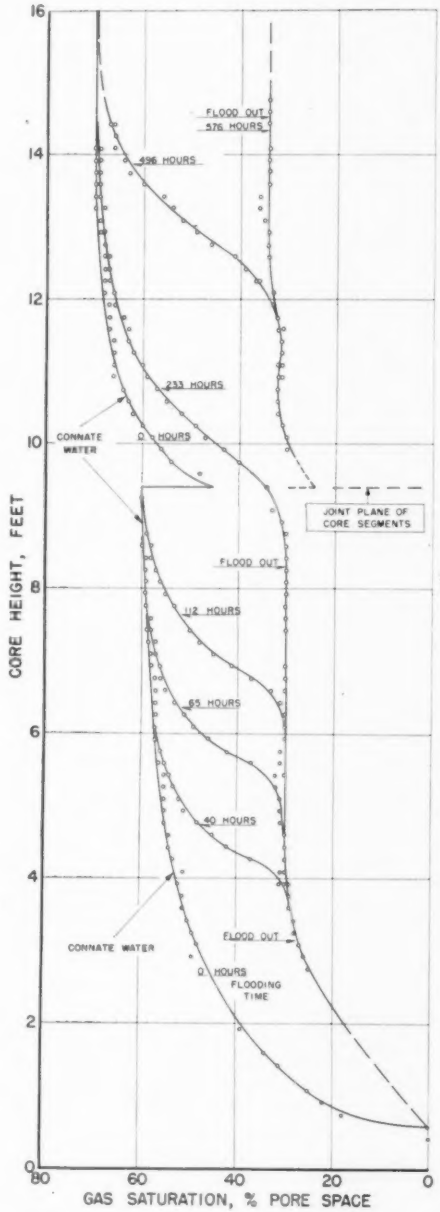

FIG. 10 — SATURATION PROFILES DURING UPDIP FLOODING OF GAS BY WATER, TORPEDO SANDSTONE.

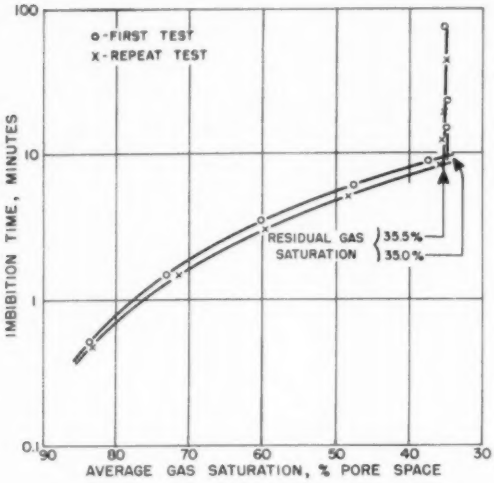

FIG. 11 — TYPICAL WATER IMBIBITION TEST DATA SHOWING REPRODUCIBILITY OF RESULTS, TORPEDO SANDSTONE. (PERMEABILITY 425 MD, POROSITY 26.5 PER CENT).

have no effect on residual gas saturation provided the flooding liquids wet the rock to the same extent.

It is concluded from the preceding data, that residual gas saturations measured on dry cores by water imbibition are essentially the same as those values measured by flow tests starting with connate water in the core.

Incidental to the main subject under discussion, a significant observation was made in these imbibition tests. All cores tested imbibed oil, but some of them would not imbibe water. These cores which were repellent to water were identified by other laboratory tests as being preferentially oil wet. Thus the imbibition test can be used to indicate wettability characteristics of rocks.

Many types of porous materials were investigated in the laboratory to evaluate the range of residual gas saturations that can be expected in reservoirs. A listing of the results of these tests is given in Table VII. The significant feature of these data is that residual gas saturations after water flooding reservoir rocks range from 16 to 50 per cent pore space, which is the same range of values for residual oil saturation obtained in the laboratory when water flooding "oil sands." Craze and Buckley[9] have determined from field data that residual oil saturations in water drive oil reservoirs are within this same range of values.

Table V — Comparison of Residual Gas Saturation Obtained by Relative Permeability and Brine Imbibition Tests

Sandstone	Residual Gas Saturation, % Pore Space	
	By Rel Perm Tests	By Imbibition
Frio	34.5	32.5
Frio	35.0	34.7
Frio	33.7	37.0
Frio	34.7	35.3
Frio	34.1	37.0
	Avg - 34.4	35.3
Nellie Bly	32.3*	30-36**
Torpedo	37.0*	34.7***

*One sample only.
**Range for 12 cores.
***Average five other samples (See Table II).

Table VI — Oil Imbibition vs Water Imbibition

Sample	Residual Gas Saturation, % Pore Space	
	By Oil Imbibition	By Water Imbibition
Selas Porcelain	16.3	17.5
Torpedo Sand	35.4	34.5
Frio Sand	34.0	34.2
Frio Sand	33.4	33.6
Frio Sand	29.8	30.2
Frio Sand	29.8	29.6

MEASUREMENT OF RESIDUAL GAS SATURATION IN WATER FLOODED GAS RESERVOIRS

Field data were reviewed to find out if residual gas saturation in watered-out gas sands could be evaluated by a material balance calculation as Craze and Buckley[9] did for residual oil in water drive oil sands. No suitable field data were located, due primarily to the fact that at this time very few water drive gas sands have been completely flooded. Also, the usual wide well spacing in gas fields makes difficult the precise determination of field areal extent, which is an important factor in the calculation of residual gas saturation. In the absence of field performance data, other means of evaluating residual gas saturation in watered-out portions of gas reservoirs were used, namely, physical measurements of gas content of cores and calculation of gas saturation using electric log data.

West Beaumont Field, Tex.

Production history and recent drilling have established that the 4,500-ft gas sand of the West Beaumont Field, Jefferson County, Tex., has been partly flooded out due to a rise in the water level as a result of production. Seeking deeper pay, a well was recently drilled in a portion of the field in which the 4,500-ft gas sand had been flooded out by water for approximately five years. The original elevation of the gas-water contact was accurately determined from the electric logs of an original gas well located 170 ft from the new well.

The 4,500-ft gas sand was cored with Carter Oil Co.'s pressure core barrel. Ten cores were cut making a total of 43 ft cored. In three of these runs the equipment operated completely satisfactorily, recovering core at the surface under bottom hole pressure. Gas volumes bled from the cores at the surface were converted to reservoir volumes, taking into account an experimentally determined compressibility factor of 0.85. Results of the tests are given in Table VIII.

Porosity values are averages of several samples from each core. These values may not reflect the true porosities that existed in the reservoir because the soft nature of the rock as the core was removed from the core barrel made it evident that it was reworked during cutting operations. This being the

Table VII — Summary of Results, Residual Gas Saturation After Water Flood as Measured on Core Plugs in Laboratory

Porous Material	Formation	Residual-Gas Saturation % Pore Space	
Unconsolidated Sand	———	16	(13-ft Column)
Slightly Consolidated Sand (Synthetic)	———	21	(1 Core)
Synthetic Consolidated Materials	Selas Porcelain	17	(1 Core)
	Norton Alundum	24	(1 Core)
Consolidated Sandstones	Wilcox	25	(3 Cores)
	Frio	30	(1 Core)
	Nellie Bly	30-36	(12 Cores)
	Frontier	31-34	(3 Cores)
	Springer	33	(3 Cores)
	Frio	30-38 (Average 34.6)	(14 Cores)
	Torpedo	34-37	(6 Cores)
	Tensleep	40-50	(4 Cores)
Limestone	Canyon Reef	50	(2 Cores)

situation, residual gas saturations calculated are minimum values, due not only to use of too large porosity values, but also to the possibility of gas bubbles escaping from the cut rock before recovery at the surface. Considering these possibilities, it is estimated that the residual gas saturation is more probably in the order of 22 per cent pore space.

It is significant to note that the higher measured value of residual gas was found in the core which was closer to the original gas-water contact which, of course, had been flooded out the greater length of time. Therefore, based on these results, it is indicated that diffusion has not been an effective means of gas removal in this sand. The core taken from below the original gas-water contact contained no gas, although it was under bottom hole pressure when retrieved at the surface.

In addition to the physical measurements, an electric log analysis was made on the watered-out gas sand. In Table VIII are values of residual gas for the three cored sections using the Archie formula[6] for calculating saturations. There are uncertainties in the electric log interpretation since the cores recovered were of such a nature that no basic electrical measurements could be made on them. The results reported are those calculated using the most reasonable values for factors involved. It was found that by varying porosity over a range of 25 to 35 per cent; cementation factor, 1.4 to 1.6; and true reservoir resistivity at 100 per cent water saturation, 0.65 to 0.85 ohm-meter; the value of residual gas for the first core reported in Table VIII ranged from 22.7 to 40.0 per cent pore space. Results from the electric log cover a wide range of values; but even by using the most extreme conditions, the residual gas saturation is of the order measured in the laboratory on cores.

The friable nature of the sand did not permit laboratory measurement of residual gas saturations by flow tests. But on similar types of material, unconsolidated to slightly consolidated sand, values from 16 to 21 per cent pore space have been measured which agree in magnitude with the physical measurements of residual gas in the West Beaumont cores.

Table VIII — Gas Saturations Measured on Cores Cut With Pressure Core Barrel

Depth Interval	Porosity	Gas Saturation Physical Measurement	Gas Saturation Electric Log Calculation
4,564	Top of Sand	—	—
4,573-77	32.9	16.7	37
4,589-93	31.0	18.5	19.4
4,600	ORIGINAL GAS - WATER CONTACT		
4,601-06	8.1	0	0

Lakeside Field, Louisiana

A well drilled in 1950 near the west edge of the Lakeside Field, Cameron Parish, Louisiana, penetrated the Siphonina Davisi sand. This reservoir had produced gas and distillate starting in 1941. Field data indicate that the reservoir has an active water drive and that the water-gas contact has moved up approximately 30 ft as a result of production. The sand logged in this new well included both the water flooded and unflooded portions of the pay. In Table IX are given calculated gas saturations using the Archie formula,[6] as well as other pertinent information concerning the well.

The calculation of gas saturations was based on a 30 per cent porosity measured on a core and the most reasonable values for other factors involved in the determination, so the numbers are subject to the usual limitation on quantitative electric log data. The drill stem test confirmed that the lower portion of the sand was flooded out, and calculations indicated that 21.8 per cent gas saturation still remained. This value is of the same order of magnitude as residual gas saturation measured in the laboratory on friable type sand samples (see Table VI).

Table IX — Analysis of Siphonina Davisi Sand Lakeside Field, Louisiana

Depth	Calc. Gas Saturation From Electric Log Data	General Data
9,978	68	—
9,974-90	—	Completion; produced gas and distillate with no water
9,998	60.9	—
10,010	—	Top of flooded-out zone at time of completion of this well (calculated from field performance data)
10,018	21.8	—
10,020-30	—	Drill stem test; recovered salt water
10,040	—	Original water-gas contact

CONCLUSIONS

1. Laboratory and field evidence both substantiate the conclusion that residual gas saturations as determined in the laboratory on core plugs are, within practical limits, the same as will occur in a gas sand under a water flood.
2. Residual gas saturations vary from 15 per cent to 50 per cent pore space for different sands, which is the same range of variations for residual oil saturations after water flooding oil sands.

ACKNOWLEDGMENTS

The authors wish to acknowledge the cooperation of the Research Department of the Carter Oil Co. in the pressure coring operation at West Beaumont and the helpful suggestions and cooperation of many individuals in the Producing

Department of Stanolind who contributed greatly to the entire investigation. Also, appreciation is expressed to the Stanolind Oil and Gas Co. for permission to present this paper.

REFERENCES

1. Geffen, T. M., Owens, W. W., Parrish, D. R., and Morse, R. A.: "Experimental Investigation of Factors Affecting Laboratory Relative Permeability Measurements," *Trans.* AIME, (1951) **192**, 99.
2. Osoba, J. S., Richardson, J. G., Kerver, J. K., Hafford, J. A., and Blair, P. M.: "Laboratory Measurements of Relative Permeability," *Trans.* AIME, (1951) **192**, 47.
3. Caudle, B. H., Slobod, R. L., and Brownscombe, E. R.: "Further Developments in the Laboratory Determination of Relative Permeability," *Trans.* AIME, (1951) **192**, 145.
4. Sewell, Ben W.: "The Carter Pressure Core Barrel," API *Drill. and Prod. Prac.*, (1939), 69.
5. Mullane, J. J.: "Pressure Core Analyses," API *Drill. and Prod. Prac.*, (1941), 163.
6. Archie, G. E.: "The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics," *Trans.* AIME, (1942) **146**, 54.
7. Gilliland, E. R.: *Ind. Eng. Chem.*, (1934) **26**, 681.
8. Hough, E. W., Rzasa, M. J., and Wood, B. B.: "Interfacial Tensions at Reservoir Pressures and Temperatures; Apparatus and the Water-Methane System," *Trans.* AIME, (1951) **192**, 57.
9. Craze, R. C., and Buckley, S. E.: "A Factual Analysis of the Effect of Well Spacing on Oil Recovery," API *Drill. and Prod. Prac.*, (1945) 144.

DISCUSSION

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The authors are to be commended for their pioneering efforts in studying the magnitude and significance of residual gas saturations obtained when gas-filled porous media are liquid flooded. The laboratory experiments described represent a major undertaking both from a standpoint of the complexity of apparatus required and also the diversity of the experiments performed. The critical issue involved in this paper is whether the imbibition distribution of saturation noted in laboratory experiments is sufficiently stable to apply to reservoir conditions of pressure, temperature and rate of water advance, and to permit a determination of the efficiency of water floods in reservoirs from laboratory data. Therefore, on such an important issue as reserves left in the ground, a critical examination of the evidence presented by the authors should be made.

No anomalous results due to boundary discontinuities can be noted in these experiments. Theoretically, boundary effects should not influence results at the residual gas saturation where the gas permeability goes to zero and the flat saturation profile shown in Figs. 5, 6, and 9 as the outflow end is approached verifies this. The good agreement obtained among the residual gas saturations in flooding experiments over a wide range of pressure and temperature with those obtained by imbibition experiments on small core samples indicates that the fast and simple imbibition experiments duplicate the laboratory flooding results. This agreement has been found in our laboratories also among results from water and oil floods at laboratory temperature and low pressures and those of immersion experiments.

Deemed particularly significant is the apparent lowering of the residual gas saturation by diffusion, Figs. 3 and 5. It should be pointed out that the relation developed by Gilliland referred to applies only to gases diffusing in gases and cannot be applied to gases diffusing in liquids, which system is involved in this case.

While the effect of temperature upon the diffusivity coefficient in Fick's Law can be approximated by the Stokes-Einstein equation $D \propto \frac{T}{\mu}$, the effect of pressure upon the diffusivity coefficient is not readily obtainable. Therefore, additional study will be required before this diffusional effect can be interpreted in terms of rate of water advance at reservoir pressure and temperature.

AUTHORS' REPLY TO MESSRS. RICHARDSON AND OSOBA

Richardson and Osoba have brought up an important point concerning the applicability of the Gilliland equation for estimating the effects of temperature and pressure on the rate of diffusion of gas. The authors fully realize that the relation was not derived for diffusion of a gas through a liquid. Unfortunately, no information is available which can be used to evaluate precisely this problem. Although Gilliland's equation cannot be used to evaluate the absolute value of the diffusivity coefficient, the upper limit of the effect of temperature and pressure on diffusion rate can be reasonably estimated. Qualitatively, the conclusion that gas diffusion in terms of saturation is of minor significance, considering the length of the producing life of a reservoir, is substantiated by the fact that residual gas saturations measured on cores cut with a pressure core barrel in the West Beaumont Field were in the range of values expected, based on other measurements made on cores in the laboratory. ★ ★ ★

DISPLACEMENT MECHANISM IN MULTI-WELL SYSTEMS

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ABSTRACT

A procedure for determining the behavior of a reservoir under a gas or water injection program was reported by Buckley and Leverett in 1942.[1] This method, which allowed the calculation of the phase saturation distribution behind the front of a displacing fluid, has been extended to apply to a more general situation.

The reservoir may initially contain flowing quantities of the displacing fluid, or the fluid in the reservoir may be above saturation pressure so that solution effects are present. Production may occur behind the front as in the case of a well which is produced after breakthrough of the displacing fluid. The calculating procedure is simplified in that the graphical integration necessary to determine breakthrough saturation is eliminated by performing a direct integration and the graphical differentiation necessary to determine saturation distribution is eliminated by representing the displacing phase fraction of the flowing stream by an empirical equation. This representation results in simple expressions for the producing gas or water/oil ratio and cumulative production.

INTRODUCTION

A method for the calculation of the saturation distribution behind the front (interface between the displaced and displacing phases in a gas injection or water flooding operation) was reported by Buckley and Leverett in 1942. The method leads to a curve for the saturation distribution which is double-valued; consequently, part of the curve was interpreted to be physically meaningless. That part of the curve which has physical significance was determined by a graphical integration (material balance).

In this paper it is shown that the integration may be performed analytically with a resulting equation for the saturation of the displacing phase at the front. The case in which the displacing fluid is initially flowing and the case in which the reservoir is initially above the saturation pressure so that some injected gas goes into solution are included in the integration. The calculations are considerably simplified by representing the fraction of the flowing stream which is oil by an exponential function of saturation.

The method is extended to apply approximately to reservoirs in which wells located between the injection well and the front are produced. An illustrative example utilizing the methods presented is included.

RESERVOIR BELOW SATURATION PRESSURE

In the case of a water flooding operation or in the case of a gas injection operation in which no gas goes into solution in the displaced oil, the equation for saturation in a linear flow system as a function of time and position as given by Buckley and Leverett is

$$\left(\frac{dx}{dt}\right)_{\rho_d} = \frac{5.61q}{fA}\,\Psi_d' \qquad (1)$$

where*

q = total reservoir volume flow rate, rvb/day
A = cross sectional area of system, sq ft
f = porosity of formation
x = distance from injection point, ft
t = time, days
ρ_d = saturation of the displacing phase
$\left(\frac{dx}{dt}\right)_{\rho_d}$ = velocity of planes of constant saturation, ft/day

[1]References given at end of paper.

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*The nomenclature used here is not the same as that used by Buckley and Leverett. A complete nomenclature is given in Appendix A.

f_d = fraction of flowing stream which is the displacing phase $= \dfrac{1}{1 + \dfrac{k_o}{k_d}\dfrac{\mu_d}{\mu_o}}$

$\Psi_d' = \dfrac{d\Psi_d}{d\rho_d}$, the change of the fraction of the flowing stream with saturation (displacing phase)

k_o = relative permeability to oil

k_d = relative permeability to the displacing phase,

$\dfrac{\mu_d}{\mu_o}$ = ratio of the viscosity of the displacing phase to the viscosity of the displaced oil.

Equation (1) and the developments presented here apply to linear flow systems. Application to actual reservoirs may be achieved approximately by considering the product fAx to be the pore volume enclosed by a surface of fixed saturation and approximately determining the shape of these surfaces by independent means. If $V = \dfrac{fAx}{5.61}$ is the pore volume in barrels enclosed by the surface of saturation ρ_d. Equation (1) may be written as

$$\left(\frac{dV}{dQ}\right)_{\rho_d} = \Psi_d' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where $Q = \int_o^t q(t)\,dt$ is the total number of barrels of injected fluid (measured at reservoir conditions)

and $\left(\dfrac{dV}{dQ}\right)_{\rho_d}$ is the change in the pore volume enclosed by the surface of saturation ρ_d per unit volume of injected fluid.

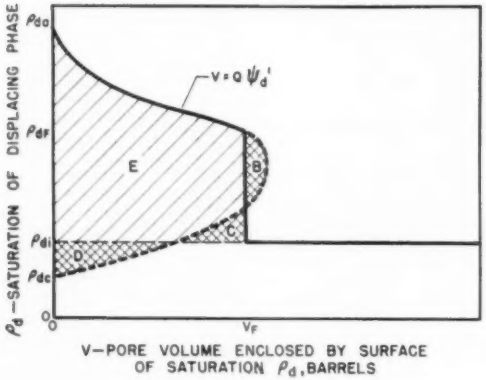

FIG. 1 — SATURATION DISTRIBUTION IN A GAS INJECTION OR WATER FLOODING OPERATION.

ρ_{dc} = Saturation at which permeability to the displacing phase goes to zero. ρ_{di} = Initial saturation of displacing phase. ρ_{df} = Saturation of displacing phase at the front. V_F = Pore volume swept out by the front. ρ_{do} = Saturation at which permeability to the displaced phase goes to zero.

If the saturation does not vary with position before injection occurs, Equation (2) may be integrated directly:

$$V = Q\,\Psi_d' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Saturation plotted *vs* V from Equation (3) for a particular Q appears as shown by the curve in Fig. 1. The dotted portion of the curve is taken to be imaginary and is determined by material balance methods.

The area enclosed by the curve and the axis $V = 0$ is equal to the volume of displacing fluid which has been injected. It can be shown (Appendix B) that the area D is equal to the volume of displacing fluid initially present which has flowed out of the volume occupied by the front; and therefore the saturation at the front is determined by making the area B equal to the area C. If the initial saturation is equal to or less than ρ_{dc} (the saturation at which permeability to the displacing phase goes to zero) the area D is zero. If the initial saturation is equal to or greater than the saturation at which the maximum occurs in the $\dfrac{d\Psi_d}{d\rho_d}$ curve, areas B and C are zero and the saturation at the front is equal to the initial saturation (there is no discontinuity at the front).

From the condition that area B equal area C an expression is obtained for the saturation existing at the front:

$$\rho_{df} - \rho_{di} = \frac{\Psi_{df} - \Psi_{di}}{\Psi_{df}'} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where

ρ_{df} = saturation of the displacing phase at the front

ρ_{di} = initial saturation of the displacing phase.

Ψ_{df} = value of Ψ_d at $\rho_d = \rho_{df}$

Ψ_{di} = value of Ψ_d at $\rho_d = \rho_{di}$

Ψ_{df}' = value of $\dfrac{d\Psi_d}{d\rho_d}$ at $\rho_d = \rho_{df}$

Equation (4) expresses the value of the saturation at the front in terms of known quantities; the initial saturation of the displacing phase (assumed constant with position) may have any value. If the initial saturation of the displacing phase is equal to or greater than the saturation at which the maximum occurs in the $\dfrac{d\Psi_d}{d\rho_d}$ curve, the correct solution of Equation (4) is: $\rho_{df} = \rho_{di}$. If the initial saturation is less than the saturation at which the maximum occurs but greater than the saturation at which the permeability to the displacing phase goes to zero, there are two solutions, $\rho_{df} = \rho_{di}$ again being a solution but the incorrect one in this case (the saturation at the front cannot be less than the saturation at which the maximum in the $\dfrac{d\Psi_d}{d\rho_d}$ curve occurs). If the initial saturation is less than the saturation at which the permeability goes to zero, there is only one solution.

RESERVOIR ABOVE SATURATION PRESSURE

If it is assumed that the reservoir fluid is instantaneously saturated at the front by the solution of gas with no further solution effects behind the front, Equations (2) and (3) may be applied to the case in which the reservoir is above the saturation pressure.

In this case the initial saturation of the displacing phase is zero and the area D of Fig. 1 is zero. To satisfy material balance considerations the area B of Fig. 1 must equal area C

plus the volume of free gas which has disappeared by going into solution. This condition is expressed as

$$\rho_{sb} = \frac{\Psi_{gF} + \dfrac{S - S_i}{\gamma\beta - S + S_i}}{\Psi'_{gF}} - (1 - \rho_w)\frac{S - S_i}{\gamma\beta - S + S_i} \quad . \quad (5)$$

where the subscript g refers to the displacing gas phase and

S = gas solubility of the saturated oil behind the front, SCF/STB

S_i = gas solubility of the original reservoir oil, SCF/STB

γ = gas conversion factor, SCF/rvb

β = formation volume factor of the saturated oil behind the front, rvb/STB

ρ_w = connate water saturation

Equation (5) (derived in Appendix C) relates the saturation of the displacing gas at the front to quantities which are known or may be measured. The viscosity of the displaced fluid which appears in Ψ_g is taken in this case to be the viscosity of the saturated oil behind the front.

Since some of the gas is going into solution at the front and since in general the solution of a given volume of gas in oil does not increase the volume of oil by that amount, the total volume flow rate ahead of the front differs from that behind the front. That is to say, in the case of a reservoir above saturation pressure the volume production rate is less than the volume injection rate even though pressure gradients are negligible. The ratio of the production rate to the injection rate is given by

$$\Gamma = \frac{\gamma\beta_i}{\gamma\beta - S + S_i} + (1 - \rho_w)\left[1 + \frac{\gamma\beta_i}{\gamma\beta - S + S_i}\right]\Psi'_{gF} \quad . \quad (6)$$

where β_i is the formation volume factor of the displaced fluid (rvb/STB) ahead of the front and Γ is the desired ratio (see Appendix E).

PRODUCTION BEHIND THE FRONT

Consider a reservoir in which gas or water is injected through a single well and production occurs from several wells in the field (some of the wells may continue production after the front of the displacing phase has passed them). The method of Buckley and Leverett may be applied approximately in this case if it be assumed that the sweepout pattern is known and that the surfaces coincident with the front as it progresses through the reservoir will later coincide with surfaces of fixed saturation. Let V_1 be the pore volume enclosed by the frontal surface when the front reaches the first well or group of wells, V_2 the pore volume enclosed by the frontal surface when the front reaches the second group of wells, and so on for V_3, V_4, —.

The preceding analysis applies for the zone $0 < V < V_1$. However, in the second zone ($V_1 < V < V_2$) and other zones after the front has entered those zones Equation (3) may not be applied because both the displacing phase and the displaced phase are entering the zone. (In the first zone only the displacing phase is injected). Furthermore, the total volume flow rate in each zone is decreased by production from wells behind the front.

If these factors are taken into account, the saturation distribution in the second zone is given by

$$V - V_1 = \Psi'_d \int_{Q_1}^{Q} (1 - q_1)\,dQ \quad . \quad . \quad . \quad . \quad . \quad (7)$$

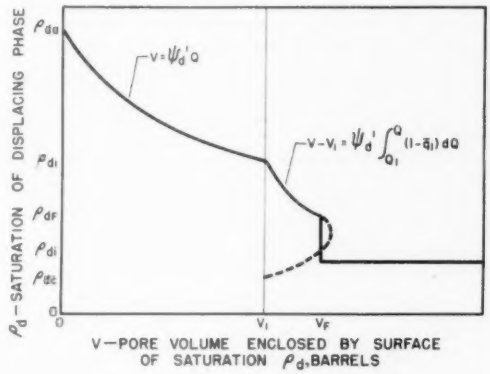

FIG. 2 — SATURATION DISTRIBUTION IN A TWO-ZONE RESERVOIR. V_1 = Pore volume of first zone. V_F = Pore volume enclosed by the front. ρ_{di} = Saturation of the displacing phase at $V = V_1$. Saturation distribution shown by solid line.

where

q_1 = fraction of total volume flow which is being voided at the first group of wells (assumed to be known)

Q_1 = volume of displacing fluid which has been injected when the surface of saturation ρ_d passes the surface $V = V_1$

The factor Q_1 may be evaluated in terms of the saturation by setting $V = V_1$ in Equation (3):

$$Q_1 = \frac{V_1}{\Psi'_d} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Equation (7) states that the volume enclosed by the surface V of saturation ρ_d is equal to the volume of the first zone plus a factor proportional to the total volume of gas and oil which has entered the second zone since the surface passed the boundary of the first zone.

The saturation distribution for a two-zone reservoir is shown in Fig. 2. There is a group of producing wells at $V = V_1$ and production has continued after the front has entered the second zone. The saturation distribution in the first zone was obtained from Equation (3) and the saturation distribution in the second zone was obtained from Equation (7). The dotted portion of the curve (between ρ_{di} and ρ_{dF}) as plotted from Equation (7) is the same as that which would have been obtained had the total volume entering the zone been gas rather than gas plus oil. The dotted portion of the curve is taken to be imaginary since the saturation at the front remains the same in the second zone as in the first (see Appendix D).

For the nth zone ($V_{n-1} < V < V_n$) the saturation distribution is given by

$$V - V_{n-1} = \Psi'_d \int_{Q_{n-1}}^{Q} (1 - q_1 - q_2 - \cdots - q_{n-1})\,dQ \quad . \quad (9)$$

where q_k is the fractional voidage rate at the kth group of wells and Q_{n-1} is the volume of displacing fluid which has been injected when the surface V of saturation ρ_d passes the $(n-1)^{th}$ group of wells.

The Q_2 which would appear in the limit of the integral if Equation (9) were applied to the third zone could be evalu-

ated in terms of saturation by setting $V = V_n$ in Equation (7). Thus by considering succeeding zones, the saturation distribution could be uniquely determined as a function of V and Q.

This procedure, however, is unwieldly unless the q_n's are constants or simple integrable functions of Q. If the integrals $\int_0^Q (1 - q_1 - q_2 - \ldots - q_{n-1})\,dQ$ cannot be evaluated directly, the variation of ρ_d with Q at each group of wells may be determined by a simple graphical procedure (it is necessary to know only the variation in saturation at each producing well in order to specify producing gas or water/oil ratio and cumulative oil production histories).

Equation (9) may written for $V = V_n$ as

$$\frac{V_n - V_{n-1}}{\Psi_d'} + \int_0^{Q_{n-1}} (1 - q_1 - q_2 - \ldots - q_{n-1})\,dQ = \int_0^{Q_n} (1 - q_1 - q_2 - \ldots - q_{n-1})\,dQ \quad . \quad . \quad . \quad . \quad . \quad (10)$$

where Q_n is the total volume of displacing fluid which has been injected when the surface of saturation ρ_d reaches the n^{th} group of wells.

If saturation is known at the $(n-1)^{st}$ group of wells as a function of the volume of gas or water injected, saturation at the n^{th} group of wells as a function of the volume injected may be determined from Equation (10) by plotting the integral $\int_0^Q (1 - q_1 - q_2 - \ldots - q_{n-1})\,dQ$ *vs* Q. For any given saturation the first term on the left hand side of Equation (10) may be directly calculated; the second term may be evaluated by referring to the plot of the integral $\int_0^Q (1 - q_1 - q_2 - \ldots - q_{n-1})\,dQ$ *vs* Q (saturation at the $(n-1)$ group of wells is known as a function of Q); the value of Q_n which will make the integral on the right side of Equation (10) equal to the left side may then be determined by referring to the plot of the integral. By considering successive zones in this manner the saturation at each group of wells as a function of the volume of gas or water injected may be readily determined and with this it is a simple matter to determine the gas/oil or water/oil ratio and production history of each well in the field.

EMPIRICAL METHODS

The calculations encountered in the application of these methods to practical uses are greatly simplified by representing the Ψ_d function by an analytical function of saturation.

Since breakthrough saturation is specified by Equation (4) or (5) and since gas or water/oil ratio and cumulative oil production at the well can be determined from the saturation existing at the well, accurate results may be obtained from any analytical representation which fits the data in the saturation range from breakthrough to abandonment saturation regardless of the fit outside this range.

A representation which greatly facilitates the calculations necessary in the type of problems under consideration here is an exponential. In all of a number of cases which have been studied it has been possible to choose a factor λ such that a plot of log $(\Psi_n + \lambda)$ *vs* ρ_d is a straight line over the range of interest (between breakthrough and abandonment saturations). That is, Ψ_d may be represented by

$$\Psi_d = 1 - \Psi_n = 1 + \lambda - \exp\left\{\frac{\theta - \rho_d}{\omega}\right\} \quad . \quad . \quad (11)$$

where ω and θ are constants and are determined by the slope and intercept of the straight portion of the log $(\Psi_n + \lambda)$ *vs* ρ_d plot.

With this representation it is only a matter of a few minutes to calculate the breakthrough saturation and the entire gas or water/oil ratio and production history once Ψ_d or Ψ_n *vs* ρ_d has been plotted.

For a water injection operation or a gas injection operation in which the reservoir initially is at or below saturation pressure, the equation for the saturation at the front becomes:

$$x = C_1 e^x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where $x = 1 + \dfrac{\rho_{df} - \rho_{di}}{\omega}$

and $C_1 = (1 + \lambda - \Psi_{di}) \exp\left\{\dfrac{\rho_{di} - \theta}{\omega} - 1\right\}$

Equation (12) may be readily solved by trial or graphical means for the factor x from which breakthrough saturation may be obtained.

In the case of a reservoir which is above the saturation pressure, the equation for the saturation at the front is:

$$y = C_2 e^y \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where $y = 1 + \dfrac{\rho_{df} + (1 - \rho_w)\dfrac{S + S_i}{\gamma\beta - S + S_i}}{\omega}$

$$C_2 = \left(1 + \lambda + \frac{S - S_i}{\gamma\beta - S + S_i}\right) \exp\left\{-\frac{1}{\omega}\left[\omega + \theta + (1 - \rho_w)\frac{S - S_i}{\gamma\beta - S + S_i}\right]\right\}$$

Equation (13) may be solved by trial for the factor y from which the value of the breakthrough saturation may be obtained.

With the exponential representation simple expressions are obtained for gas or water/oil ratio and cumulative production at the producing well since Ψ_d varies linearly with Ψ_d' and hence the fraction of the flowing stream which is oil at any well may be determined easily as a function of Q.

For example, the cumulative oil production at the first group of wells is given by

$$N = N_b + \frac{1}{\beta}\int_{Q_b}^{Q} q_t \Psi_n(\rho_{di})\,dQ = N_b + \frac{1}{\beta}\int_{Q_b}^{Q} q_t\left(\frac{\omega V_s}{Q} - \lambda\right)dQ \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where N = cumulative oil production, STB
N_b = cumulative oil production at breakthrough, STB
Q_b = volume of displacing fluid which has been injected when breakthrough occurs, rvb.

Since q_t is known as a function of Q, Equation (14) expressly defines the cumulative oil production at the first group of wells as a function of the amount of displacing fluid which has been injected.

As another example, the gas/oil ratio at the first group of wells after breakthrough in a gas injection operation is given by

$$R = \frac{\Psi_g}{\Psi_n}\gamma\beta + S = \frac{\gamma\beta Q}{V_s\omega - \lambda Q} - \gamma\beta + S \quad . \quad . \quad . \quad . \quad (15)$$

where R is the gas/oil ratio, SCF/STB.

ILLUSTRATIVE EXAMPLE

Since this paper is intended primarily for the use of practical engineers, a numerical example illustrating the use of the methods proposed here will be given in detail. The case to be considered is a reservoir initially above saturation pressure with production occurring behind the front. The constants of the system are listed below:

Fluid Properties

	Initial	Flooded Volume
oil viscosity μ_o	0.93 cp	0.60 cp
gas viscosity μ_g		0.022 cp
gas solubility S	400 $\frac{\text{SCF}}{\text{STB}}$	600 $\frac{\text{SCF}}{\text{STB}}$
formation volume factor β	1.20 $\frac{\text{rvb}}{\text{STB}}$	1.32 $\frac{\text{rvb}}{\text{STB}}$
gas conversion factor γ		1160 $\frac{\text{SCF}}{\text{rvb}}$

The values shown are obtained by measurements on the initial under-saturated oil and on oil just brought to the saturation point by the addition of gas.

Reservoir Properties

$V_1 = 29 \times 10^6$ bbl = Pore volume swept by front when injected gas breaks through the first group of producing wells.

$V_2 = 66 \times 10^6$ bbl = Pore volume swept by front when injected gas breaks through second group of producing wells.

$q_i = \frac{2}{3}$ before breakthrough.
$= \frac{1}{3}$ after breakthrough.
= total production rate of first group of producing wells relative to gas injection rate (measured on reservoir volume basis).

$\rho_w = 0.40$ = connate water saturation.

Relative Permeability

ρ_g	0.15	0.20	0.25	0.30	0.35
k_g/k_o	0.043	0.208	0.796	3.30	31.6
Ψ_o	0.460	0.150	0.044	0.011	0.0016

The curve marked $\lambda = 0$ in Fig. 3 is the plot of gas saturation *vs* log Ψ_o. The curve marked $\lambda = 0.0039$ is a plot of gas saturation *vs* log $(\Psi_o + 0.0039)$; since this curve is straight over a large range, λ is taken to be equal to 0.0039 for this example.

The constant θ is given by the intercept of the straight portion of the curve and the ordinate $\Psi_o + \lambda = 1$; here $\theta = 0.12$.

The constant ω is given by the negative of the slope of the straight portion; in this example $\omega = 0.0426$.

The fraction of the flowing stream which is oil is then represented by

$$\Psi_o = e^{\frac{0.12 - \rho_g}{0.0426}} - 0.0039$$

Breakthrough saturation is calculated from Equation (13). The constant C_2 in Equation (13) has the value 0.00305. The value of γ which satisfies Equation (13) in this case is 7.87. Then

$$1 + \frac{\rho_{gF} + (1 - 0.40)\,\frac{600 - 400}{(1160)(1.32) - 600 + 400}}{0.0426} = 7.87$$

or $\rho_{gF} = 0.203$

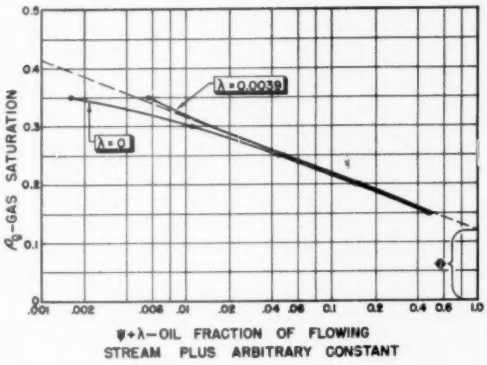

FIG. 3 — GAS SATURATION PLOTTED AGAINST LOG $(\Psi_o + \lambda)$ FOR ILLUSTRATIVE EXAMPLE.
With $\lambda = 0.0039$, curve is practically straight over a wide range. The constant θ is determined by the value of saturation when $\Psi_o + \lambda = 1$.

and $\Psi'_{gF} = \frac{1}{\omega} e^{\frac{\theta - \rho_{gF}}{\omega}} = 3.36$

The amount of gas which has been injected when breakthrough occurs at the first group of wells is obtained from Equation (3):

$$Q_{ib} = \frac{V_1}{\Psi'_{gF}} = \frac{29 \times 10^6}{3.36} = 8.65 \times 10^6 \text{ rvb} = 10.0 \times 10^6 \text{ SCF gas.}$$

The gas/oil ratio at the first group of wells after breakthrough is given by Equation (15).

$$R_i = \frac{1530\,Q}{1.235 \times 10^6 - 0.0039\,Q} - 930 \quad \frac{\text{SCF}}{\text{STB}}$$

The wells in this field are abandoned at a gas/oil ratio of 30,000 $\frac{\text{SCF}}{\text{STB}}$; the amount of gas which has been injected when the first group of wells is abandoned is determined by setting $R_i = 30{,}000$:

$Q_{ia} = 23.2 \times 10^6$ rvb $= 26.9 \times 10^6$ SCF gas.

The cumulative oil production of the first group of wells at breakthrough is

$$N_{ib} = \frac{(q_i)(Q_{ib})}{\beta_i} = \frac{(2/3)(8.65 \times 10^6)}{1.20} = 4.80 \times 10^6 \text{ STB oil.}$$

After breakthrough the cumulative oil production of the first group of wells is given by Equation (14):

$$N_1 = 4.80 \times 10^6 + \frac{1}{1.32} \int_{8.65 \times 10^6}^{Q} \frac{1}{3} \left[\frac{(0.0426)(29 \times 10^6)}{Q} - 0.0039 \right] dQ$$

$$= 4.89 \times 10^6 + (0.312 \times 10^6) \log \frac{Q}{8.65 \times 10^6} - 9.85 \times 10^{-4}\, Q \text{ STB}$$

At abandonment ($Q = 23.2 \times 10^6$ rvb) cumulative production is

$N_{1a} = 5.17 \times 10^6$ STB oil

The saturation distribution in the reservoir zone between the first and second group of wells after the first group of wells has been abandoned is determined from Equation (7):

$$V - V_1 = \Psi_g' \left\{ \int_{Q_1}^{Q_{1a}} (1-1/3)\,dQ + \int_{Q_{1a}}^{Q} (1-0)\,dQ \right\}$$

$$= \Psi_g' \left\{ \int_{\frac{V_1}{\Psi_g'}}^{Q_{1a}} 2/3\,dQ + \int_{Q_{1a}}^{Q} dQ \right\}$$

$$\text{or } V - \frac{1}{3}V_1 = \Psi_g' \left(Q - \frac{1}{3}Q_{1a}\right)$$

for saturation less than abandonment saturation.

The amount of gas which has been injected when breakthrough occurs at the second group of wells is obtained by setting $V = V_2$:

$$Q_{2a} = 24.5 \times 10^6 \text{ rvb} = 28.4 \times 10^6 \text{ SCF gas}$$

[Note: If breakthrough at the second group of wells had occurred before abandonment of the first group of wells, it would be necessary to determine the saturation distribution existing in the second zone before abandonment of the first group of wells.]

The gas/oil ratio (constant before breakthrough) at the second group of wells after breakthrough is given by:

$$R_2 = \frac{\Psi_g'}{\Psi_o}\gamma\beta + S = \frac{\gamma\beta}{\omega\Psi_g' - \lambda} - \gamma\beta + S$$

$$= \frac{\gamma\beta}{\omega\left(\dfrac{V_2 - 1/3\,V_2}{Q - 1/3\,Q_{1a}}\right) - \lambda} - \gamma\beta + S$$

$$= \frac{1530\,(Q - 7.33 \times 10^6)}{2.43 \times 10^6 - 0.0039\,Q} - 930$$

The amount of gas injected when the gas/oil ratio is 30,000 $\frac{\text{SCF}}{\text{STB}}$ is:

$$Q_{2a} = 52.4 \times 10^6 \text{ rvb} = 60.7 \times 10^6 \text{ SCF gas}$$

The ratio of the total volume flow rate head of the front to that behind the front is obtained from Equation (6):

$$\Gamma = \frac{(1160)\,(1.20)}{(1160)\,(1.32) - 600 + 400} + (1 - 0.40)$$

$$\left[1 - \frac{(1160)\,(1.20)}{(1160)\,(1.32) - 600 + 400}\right](3.36) = 0.952$$

At breakthrough in the first group of wells 8.65×10^6 rvb of gas had been injected but only $(0.952)\,(8.65 \times 10^6) = 8.24 \times 10^6$ rvb of oil had been produced. Since $2/3\,(8.65 \times 10^6)$ rvb were produced at the first group of wells, the production at the second group of wells was 2.47×10^6 rvb or 2.06×10^6 STB oil.

At abandonment of the first group of wells 23.2×10^6 rvb of gas had been injected or 14.6×10^6 rvb since breakthrough. One third of this volume was voided at the first group of wells in the form of both gas and oil with 2/3 or 9.73×10^6 rvb entering the second zone. Hence, the production from the second group of wells during this phase is $(0.952)\,(9.73 \times 10^6) = 9.26 \times 10^6$ rvb or 7.72×10^6 STB oil. During the phase of production between abandonment of the first group and breakthrough at the second group of wells a total of 1.3×10^6 rvb of gas was injected which corresponds to $(0.952)\,(1.3 \times 10^6) = 1.24 \times 10^6$ rvb or 1.03×10^6 STB of oil production.

The total cumulative production of the second group of wells at breakthrough is then $(2.06 + 7.72 + 1.03) \times 10^6 = 10.81 \times 10^6$ STB of oil.

After breakthrough, the cumulative oil production is given by

$$N_2 = 10.81 \times 10^6 + \frac{1}{\beta}\int_{24.5 \times 10^6}^{Q} \Psi_o\,dQ$$

$$= 10.81 \times 10^6 + \frac{1}{1.32}\int_{24.5 \times 10^6}^{Q} \left[\frac{\omega(V - 1/3\,V_1)}{Q - 1/3\,Q_{1a}} - \lambda\right] dQ$$

$$= 10.88 \times 10^6 - 0.00296\,Q + 1.82 \times 10^6 \log \frac{Q - 7.73 \times 10^6}{16.8 \times 10^6}$$

The cumulative production at abandonment is obtained by setting $Q = 52.4 \times 10^6$:

$$N_{2a} = 12.51 \times 10^6 \text{ STB}$$

The total production for the field is $12.51 \times 10^6 + 5.17 \times 10^6 = 17.68 \times 10^6$ STB oil.

ACKNOWLEDGMENTS

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REFERENCES

1. Buckley, S. E., and Leverett, M. C.: "Mechanism of Fluid Displacement in Sands," *Trans.* AIME, (1942) **146**, 107.

APPENDIX A — NOMENCLATURE

A	Cross sectional area, sq ft
f	Porosity
k	Relative permeability, md/md
N	Cumulative oil production, STB
q	Total reservoir volume flow or injection rate, rvb/day
q_n	Total reservoir volume production rate of the n^{th} group of wells relative to injection rate $\frac{\text{rvb/day}}{\text{rvb/day}}$
Q	Total volume of fluid injected, rvb
R	Gas/oil ratio, SCF/STB
S	Gas solubility factor, SCF/STB
t	Time, days
V	Pore volume enclosed by surface of fixed saturation, rvb
x	Distance from injection point, ft
β	Formation volume factor, rvb/STB
γ	Gas conversion factor, SCF/rvb
Γ	Ratio of flow rate ahead of front to flow rate behind front
θ	Constant
λ	Constant
μ_o/μ_w	Viscosity ratio of displacing phase to displaced phase, cp/cp
ρ	Saturation
Ψ	Fractional flowing stream
ω	Constant

Subscripts

b	Breakthrough
d	Displacing phase
g	Gas
i	Initial
m	Mean
n	Number
o	Oil
w	Water

APPENDIX B — BREAKTHROUGH SATURATION — RESERVOIR BELOW SATURATION PRESSURE

Referring to Fig. 1, the area enclosed by the curve and the axis $V = 0$ is

$$\int_{\rho_{di}}^{\rho_{da}} Q\,\Psi_d'\,d\rho_d = Q = E + B + D$$

The area D is

$$D = \int_{\rho_{di}}^{\rho_{di}} Q\,\Psi_d'\,d\rho_d = Q\Psi_{di}$$

= volume of displacing fluid which has flowed out of the volume V_p.

The area E plus C must equal the volume of injected fluid less the volume of displacing fluid which has flowed out of the volume V_p or $Q - D$.

Therefore area B must equal area C. The condition that area C equal area B is

$$E + B = Q - D = E + C$$
$$= V_p(\rho_{dF} - \rho_{di}) + \int_{\rho_{dF}}^{\rho_{da}} Q\Psi_d'\,d\rho_d$$
$$= Q\Psi_{dF}'(\rho_{dF} - \rho_{di}) + Q(1 - \Psi_{dF})$$

from which

$$\rho_{dF} = \rho_{di} + \frac{\Psi_{dF} - \Psi_{di}}{\Psi_{dF}'}$$

APPENDIX C — BREAKTHROUGH SATURATION — RESEVOIR ABOVE SATURATION PRESSURE

Referring to Fig. 1, area D is zero for this case and area E plus C must equal the volume of gas which has been injected less the volume of gas which has gone into solution. Therefore, area B must equal area C plus the volume of gas which has gone into solution.

The volume of gas which has gone into solution may be determined by considering the quantity of oil left behind the front. The volume of oil left behind the front is

$$V_p\,\rho_{om} = \Psi_{gF}'\,Q(1 - \rho_w - \rho_{gm})$$

where ρ_{om} is the mean oil saturation behind the front and ρ_{gm} is the mean free gas saturation behind the front. Now,

$$\rho_{gm} = \rho_{gF} + \frac{1}{V_p}\int_{\rho_{dF}}^{\rho_{da}} Q\Psi_{gF}'\,d\rho_g = \rho_{gF} - \frac{1 - \Psi_{gF}}{\Psi_{gF}'}$$

Then, the volume of oil left behind the front is

$$\Psi_{gF}'\,Q\left(1 - \rho_w - \rho_{gF} - \frac{1 - \Psi_{gF}}{\Psi_{gF}'}\right)$$

The amount of gas originally in solution in this volume of oil is $\Psi_{gF}'\,Q\rho_{om}\dfrac{S_i}{\beta}$ SCF. The amount of gas in solution in this volume of oil after it is saturated is $\Psi_{gF}'\,Q\rho_{om}\dfrac{S}{\beta}$ SCF. The volume of gas which has gone into solution in this volume of oil is the difference of these divided by the gas conversion factor: $\Psi_{gF}'\,Q\rho_{om}\dfrac{S - S_i}{\gamma\beta}$ rvb.

Then area B must equal area C plus the factor

$$\Psi_{gF}'\,Q\left(1 - \rho_w - \rho_{gF} - \frac{1 - \Psi_{gF}}{\Psi_{gF}'}\right)\frac{S - S_i}{\gamma\beta}$$

or,

$$Q\Psi_{gF}'\rho_{gF} + Q(1 - \Psi_{gF}) + Q\Psi_{gF}'\left(1 - \rho_w - \rho_{gF} - \frac{1 - \Psi_{gF}}{\Psi_{gF}'}\right)\frac{S - S_i}{\gamma\beta}$$
$$= Q$$

from which

$$\rho_{gF} = \frac{\Psi_{gF} + \dfrac{S - S_i}{\gamma\beta - S + S_i}}{\Psi_{gF}'} - (1 - \rho_w)\frac{S - S_i}{\gamma\beta - S + S_i}$$

APPENDIX D — BREAKTHROUGH SATURATION — PRODUCTION BEHIND THE FRONT

The solution as given by Equation (7) for the saturation distribution in the second zone is equivalent to the solution for a one-zone reservoir in which both gas or water and oil are injected so that the saturation of the displacing phase at the injection point varies from ρ_{dF} to ρ_{da} in a known manner with time. That is, Equation (7) may be written as

$$V - V_i = \Psi_d'\,[P(Q) - \phi_d(\rho_d)]$$

where

$$P(Q) = \int_{Q_b}^{Q}(1 - q_i)\,dQ$$

= total volume of both gas or water and oil which has entered the zone since breakthrough

and $\phi_d(\rho_d) = \int_{Q_b}^{Q_i}(1 - q_i)\,dQ.$

ϕ_d is a function of ρ_d such that it describes the variation of the saturation at the boundary of the two zones with quantity injected when V equals V_i.

The area enclosed by the curve and the line $V = V_1$ in Fig. 2 is

$$\text{Area} = \int_{\rho_{d_{sc}}}^{\rho_{dF}} \Psi_d' P d\rho_d + \int_{\rho_{dF}}^{\rho_{d_1}} \Psi_d' (P - \phi_d) d\rho_d$$

$$= \Psi_d P \Big]_{\rho_{d_{sc}}}^{\rho_{dF}} + \Psi_d (P - \phi_d) \Big]_{\rho_{dF}}^{\rho_{d_1}} + \int_{\rho_{dF}}^{\rho_{d_1}} \Psi_d \frac{d\phi_d}{d\rho_d} d\rho_d$$

$$= \int_{Q_b}^{Q} \Psi_d \frac{dP}{dQ} dQ$$

$$= \int_{Q_b}^{Q} \Psi_d (\rho_{d_1})(1 - q_1) dQ$$

= total volume of the displacing phase which has entered the zone.

Since the area enclosed by the curve is equal to the total volume of the displacing phase which has entered the zone and since the dotted portion of the curve is a multiple of the curve obtained for the first zone, the same relation must hold here for the areas identified as B and C in Fig. 1 and therefore the saturation at the front is the same in the second zone as in the first.

In a similar manner it may be shown that the saturation at the front does not change as the front progresses through the remaining zones.

APPENDIX E—RATIO OF FLOW RATES AHEAD OF AND BEHIND THE FRONT

Consider a small fixed section containing the front. The difference in the rates at which gas enters and leaves this section must be equal to the rate of accumulation of gas in the section; *i.e.*,

$$\gamma \Psi_{gF} q + \frac{S}{\beta} \Psi_{wF} q - \frac{S_i}{\beta_i} \Gamma q = \left[\gamma \rho_{gF} + \frac{S}{\beta} \rho_{wF} - \frac{S_i}{\beta_i} (1 - \rho_w) \right] \frac{fA}{5.61} \frac{dx_F}{dt}$$

$$\text{or } \left(\gamma - \frac{S}{\beta} \right) \Psi_{gF} + \left(\frac{S}{\beta} - \Gamma \frac{S_i}{\beta_i} \right) =$$

$$\left[\left(\gamma - \frac{S}{\beta} \right) \rho_{gF} + (1 - \rho_w) \left(\frac{S}{\beta} - \frac{S_i}{\beta_i} \right) \right] \Psi_{gF}'$$

This equation must lead to the same expression for ρ_{gF} as that given by Equation (5); a comparison shows that Γ must be equal to the expression given by Equation (6). ★ ★ ★

THE QUANTITATIVE ASPECTS OF ELECTRIC LOG INTERPRETATION

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ABSTRACT

While intensive research continues to promote a more complete understanding of the potential and resistivity measurements that comprise the electric log, it is believed that consideration should also be given to translating these numerous and often widely separated findings into a coordinated and readable body of fundamental facts designed specifically for the petroleum engineer and geologist. Although provision is made through publication for a ready exchange of new theoretical concepts, it is also desirable to provide reviews and appraisals of the more established techniques and methods from the operating standpoint so that an economic and practical application may be realized concurrently with the theoretical progress. With these basic premises as a guide the author reviews the present state of electric log interpretation.

The paper is directed not so much to the logging or research specialist as to the petroleum engineer and geologist to whom the electric log is only one of the many tools which he employs. Frequently, these persons do not have the time to follow in detail the many specialized contributions that appear and, as a consequence, are not in a position to place these contributions in proper relation to each other, or to the art as a whole.

The paper reviews the basic steps in making quantitative determinations from the electric log of the amount of oil or gas present in subsurface formations and also discusses the degree of reliability of these determinations under various conditions. The paper also indicates the trend of future developments in electric logging systems and methods of interpretation.

INTRODUCTION

The electric log has been used about 20 years as a means for studying the formations penetrated by a well bore. The first half of this period is characterized by the development of suitable logging techniques and equipment. Although progress in this direction is continuing at a satisfactory rate, the last ten years are characterized more by an increasing interest in methods of electric log interpretation. During this period, a large number of fundamental papers have been published, expounding various logging techniques and particular phases of the interpretation problem. Many of these papers represent important contributions, and a few are classic.

This paper is an effort to outline as concisely as possible and in simple terms the main course of progress in electric log interpretation. More specifically, it is the purpose of the paper to review the necessary elements and basic steps used in making quantitative determinations of water saturation from the electric log; and to point out the degree of reliability of these determinations under different conditions.

It is strongly advised that the operating staffs of the drilling and exploration departments of oil companies cooperate wholeheartedly with both the electric logging service companies and research organizations in the testing and development of new logging systems and interpretation methods. One purpose of the paper is, however, to indicate the degree of caution which must be exercised in placing confidence in new techniques and interpretation methods that have not been thoroughly tested in the field. It is entirely possible to be cooperative in trying new methods and yet reluctant to believe in the results until the methods are firmly established.

It is important to define the meaning of quantitative electric log interpretation. In the most general sense, an interpretation of the log has been made when the electrical characteristics of the formations, as portrayed on the log, have been translated into terms describing the formation geometry, rock type, or any other physical characteristics of the formations. The determination that the top of a sand is at a certain depth is an interpretation of the log. Structural determinations made by correlating electric logs from a given area are also interpretations of the logs. The term quantitative interpretation, however, will be used in this paper in the restricted sense to indicate the determination of the water saturation of a formation. This determination defines the fluid content of an oil and gas productive formation only if the porosity is known, and it assumes that the remainder of the pore space contains hydrocarbons. This assumption is believed to be true for most oil and gas productive formations. The quantitative electric log interpretation may be said to be a determination of the fluid content only to the extent which the water saturation, under the conditions given above, defines it.

THE BASIC STEPS

The fundamental steps in calculating water saturation from the electric log are:

1. Determination of the true resistivity of the formations from the apparent resistivities as recorded on the electric log.

[1]References given at end of paper.

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2. Determination of the water saturation of the formations from the true resistivities.

Having taken these steps, and having considered the results in conjunction with other available data, it then becomes possible to:

3. Predict the type and possibly the amount of fluid production from the formations, or:
4. Utilize the determination of water saturation in calculating reserves, planning remedial operations, or making a stratigraphic or structural analysis.

Steps 1 and 2 comprise the determination of water saturation; steps 3 and 4 comprise the practical application of this determination. Although the quantitative interpretation has several uses, some of which are outlined in step 4, this paper is more specifically concerned with steps 1 and 2 and with the practical application of the quantitative determination of water saturation as indicated in step 3. The results of step 3 are of considerable value when deciding what zones to include in the production when completing a development well and when evaluating the formations exposed in an exploratory well.

In all of the steps indicated above, information obtained by other logging and testing methods is almost invariably used to supplement the electric log information. This is particularly true of steps 3 and 4. This coordinated use of the several sampling, testing and logging methods, in order to obtain the most efficient evaluation of the production possibilities of formations, has been previously reviewed.[1] Therefore, "interpreting" the electric log usually implies using all of the information that is available.

The dynamic characteristics of a reservoir, as evidenced by its ability to produce fluid, are not well resolved by means of the electric log. Adequate formation pressure, for instance, is necessary for a reasonable production of fluid but is not evaluated by the electric log. Expressed simply; what is in a sand, and what will come out of it are often two different matters. The electric log pertains chiefly to the former.

DETAILS OF STEP 1 — TRUE RESISTIVITY

Determination of true resistivity from apparent resistivity, as noted above, is the first step in calculating water saturation from the electric log. There are three factors which cause the resistivity, as indicated on any of the resistivity curves, to differ from the true electrical resistivity of the formations. These factors are:

1. Hole effect: the effect of the presence of a conductive column of drilling fluid.
2. Invasion effect: the effect of the presence of an invaded zone of formation around the well bore. This zone, which may vary in extent from a few inches to several feet, is invaded with drilling fluid filtrate. Its electrical resistivity is ordinarily different from that of the uninvaded formation.
3. Bed thickness effect: the effect of the presence of neighboring strata. Since the electrical measuring system used has a finite length, and since the thicknesses of the subsurface strata may or may not be large in comparison to that length, the measurement that is made is often affected by more than one stratum. In this case, the apparent resistivity is characteristic not of one stratum but of several.

These three effects must generally be considered. Since they are interdependent they must be corrected for simultaneously. In many instances one or more of these perturbing effects may be of minor importance, in which case consideration need be given only the remaining factors. Part of the art of electric log interpretation lies in knowing which of these effects are important for any given conditions. Thus:

1. Hole effect, in noninvaded formations, is not pronounced for the 10 and 20 ft three-electrode systems, provided the formation resistivity is not greater than about ten times the drilling fluid resistivity. This implies a conventional water base drilling fluid and hole size.
2. Invaded zone effect is not pronounced when the invaded zone resistivity is nearly equal to the true resistivity. It is also not important when the depth of invasion of the filtrate is very small.
3. Bed thickness effects decrease in importance as the thickness of the stratum increases beyond several times the length of the electrode system employed, and are usually of less importance in low resistivity media than in high resistivity media.

Hole Effect — The Effect of the Conductive Column of Drilling Fluid

When considering the effect of the mud column, it is necessary to know the diameter of the hole and the resistivity of the drilling fluid opposite the formation being studied. When dealing with fairly well consolidated sandstone formations, or other formations that do not cave, the diameter of the drill bit may be used as an approximation of the diameter of the hole. It is believed that the error introduced in this manner is usually not serious. If any doubt exists concerning the validity of this approximation, it may be removed by running a hole caliper device. The error introduced into the determination of true resistivity from the long spacing three-electrode curves, due to a ten per cent error in the diameter of the hole, will probably be small in comparison to errors introduced from other sources. The running of a caliper device is probably warranted in exploratory drilling, where the nature of the formations is unknown, and where the caliper curve may assist in other ways than that mentioned above.

The resistivity of the drilling fluid opposite the formation is obtained from the resistivity of a drilling fluid sample as measured at the surface, and the bottom hole temperature as recorded by a maximum reading thermometer when running the electric log survey. If the formation lies some distance above the bottom of the hole, it is desirable to calculate a reduced temperature, subtracting the appropriate amount from the bottom hole temperature. Charts are provided that readily convert the drilling fluid resistivity from the surface temperature to the temperature opposite the formation.

Invasion Effect — Effect of the Invaded Zone

If the resistivity of the invaded zone differs considerably from that of the uninvaded formation, there will usually be a corresponding difference between the apparent resistivity as recorded by a very short spacing system, and that recorded by a long spacing system which reflects more nearly the true resistivity of the uninvaded formation. This is important from the standpoint that invasion implies permeability and shows at least one reason why it is desirable to record more than one resistivity curve.

The parameters that describe the invaded zone cannot be determined accurately. The extent of invasion, for instance, depends upon:

1. The density and type of the drilling fluid.
2. The rate of drilling.
3. The duration of the exposure of the formations to the drilling fluid.
4. The permeability and porosity of the formations.

Although the nature of the invaded zone has been studied[2] much remains to be learned. The mixing of the drilling fluid

filtrate and formation water and the displacement of oil in the invaded zone must be taken into account. Attempts have been made to utilize quantitatively invaded zone measurements,[3] but these have not been established on a firm basis and cannot be depended on in the general case. This does not condemn the use of such special methods under those particular conditions in which they are known to give fairly good results.

The short spacing two-electrode curve (usually 10 in. or 16 in.) is ordinarily used to indicate the nature of the invaded zone, and consequently can be used to show the absence or presence of permeability. It can also be used to detect the presence of oil in the invaded zone. Furthermore, since its spacing is small, it is less affected by bed thickness effects and thus gives a more correct picture of the geometry of the sedimentation than the longer spacing systems.

The true resistivity of the uninvaded formation is best determined by employing a sufficiently long spacing to minimize the influence of the well bore and the invaded zone. This is possible under certain conditions and provided the formation is much thicker than the electrode spacing employed. This will be discussed more fully in a following section.

Bed Thickness Effect — Effect of Neighboring Strata

The influence of neighboring strata is a very complicated effect, since their thicknesses and resistivities all enter into the problem. In fact, even the simplest case: that of a single sand of finite thickness lying in an infinite shale and penetrated by a well bore of uniform diameter and resistivity, has not lent itself to accurate calculation by analytical methods. Approximate methods of calculation and model experiments have nevertheless resulted in demonstrating bed thickness effects for this simple case for two-electrode systems.[4] Unfortunately, the relationships that have been published up to the present time do not apply to the long spacing three-electrode systems that are commonly employed.

If the length of an electrode system is small in comparison to the thickness of a formation, the apparent resistivity recorded opposite that formation will be determined by the true formation resistivity, the invaded zone effect, and the hole effect. If, however, the thickness of the formation is less than two or three times the length of the spacing, neighboring formations affect the reading of apparent resistivity.

Bed thickness effects probably introduce the most serious error in the calculation of true resistivity. This is particularly true for beds less than 30 or 40 ft in thickness. Much progress will probably be made in the next few years toward improving our knowledge of bed thickness effects and designing electric logging systems that are less susceptible to these effects. The latter has to some extent already been accomplished by developing systems of electric logging that tend to confine the current distribution to a horizontal segment of formation.[5,6]

As far as bed thickness effects are concerned, it is desirable to use an electrode spacing small in comparison to the thickness of the average stratum. From the standpoint of determining true resistivity, however, it is desirable to use a long electrode spacing so that the region of the investigation is composed primarily of uninvaded formation. These two requirements are opposed to each other and may be said to be the dilemma of electric logging systems. This condition of diametrically opposed requirements again demonstrates the desirability of recording more than one apparent resistivity curve. The small spacing curve provides a means for studying the hole and invasion effects and the long spacing curves are primarily used for determining the true resistivity. If the bed is sufficiently thick, it is desirable to use the longest spacing for the true resistivity determination and the intermediate length spacing as a check. In beds of somewhat restricted thickness, one must frequently depend upon the intermediate spacing curve for the true resistivity determination. The two long spacing curves thus supplement each other in their findings.

In thin beds, of much less than 30 or 40 ft in thickness, it is at present often impossible to determine the true resistivity with a satisfactory degree of accuracy.

The Departure Curves

Departure curves permit the determination of true resistivity for various values of electrode spacing, apparent resistivity, invaded zone resistivity, drilling fluid resistivity, bed thickness, and hole diameter. Separate curves are provided for various values of the diameter of the zone of invasion. Departure curves for infinitely thick beds are available for both two-electrode and three-electrode systems. Unfortunately, curves that apply to a finite thickness of stratum are for the most part available only for two-electrode systems. This is a particular disadvantage in California where both of the long spacing electrode systems are of the three-electrode type. When using the departure curves referred to above, it is particularly important to read the limitations that are imposed on their application, as outlined at the beginning of the publication.

One factor that limits the successful application of departure curves is the difficulty of being able to choose proper values for the effective diameter of the invaded zone and its effective resistivity. The properties of the invaded zone are not uniform throughout its cross-section and therefore effective values must be chosen which most accurately represent the true conditions. Another limitation, and one of a more general nature, results as a consequence of the large number of parameters describing the problem, some of which are not known accurately. Consequently, the application of departure curves to the determination of true resistivity sometimes causes a feeling of doubt concerning the accuracy of the results. This is particularly true if one must determine resistivity from three-electrode curves since, in this case, there are only those curves for infinitely thick beds.

In order to gain a good understanding of the relative magnitude of invasion and bed thickness effects, it is suggested that the engineer or geologist study carefully the departure curves. He may, for instance, by choosing several values for the diameter of the invaded zone, determine the effect of various amounts of invasion on the electric log. By solving many examples of this sort it is possible to learn much about the effect on apparent resistivity due to the presence of the mud column, invaded zone, and neighboring strata. Knowledge gained in this manner is of value in determining when these effects are of a serious nature, and when they may be safely neglected.

A person well acquainted with the fundamental behavior of electric logging systems might, in a particular case, decide to formation test knowing that an electric log interpretation would in any case be unreliable. This fact alone can be of considerable economic significance. It is not only important to know what the electric log can do, but is equally important to know its limitations. Disregard of these limitations may be as serious, if not more so, than an ignorance concerning the basic fundamentals.

DETAILS OF STEP 2 — DETERMINING WATER SATURATION

Once the value of true formation resistivity has been determined as closely as possible, it is used in obtaining the water saturation.

The relationship between the electrical resistivity and water saturation of rocks has been studied extensively. Electrical conduction in rocks is electrolytic in nature and takes place in the water channels. The resistivity of a clean sand, free of argillaceous material, is determined by the amount of interstitial water per unit volume of sand, the electrical resistivity of the interstitial water, and the manner of distribution of the water channels in the sand. It has been shown[2] that the resistivity of such a sand saturated 100 per cent with a brine solution is proportional to the resistivity of the brine solution and may be expressed by:

$$R_o = FR_w \quad \ldots\ldots\ldots\ldots \quad (1)$$

where R_o represents the electrical resistivity of the brine saturated sand, R_w represents the resistivity of the brine solution, and F is a formation resistivity factor; or, more briefly, formation factor. The relationship has been verified over a considerable range of porosities and salinities.

As would be expected from the above considerations, the formation factor depends upon the porosity of the sand and the manner in which the void space is distributed throughout the sand. The formation factor is a unique parameter which assists in describing the physical nature of the sand. It is dimensionless and may, for a clay free sand, be defined as the ratio of the resistivity of the fully saturated sand to the resistivity of the brine solution filling its pores. It is by taking the ratio of these resistivities, as determined experimentally in the laboratory, that the formation factor of such a sand is determined.

By displacing various amounts of the water in the interstices of a fully wet clay-free sand with a nonconducting fluid such as oil, it has been demonstrated[3] that the true resistivity and water saturation may be empirically related by the following equation:

$$R_t = R_o S^{-n} \quad \ldots\ldots\ldots\ldots \quad (2)$$

where S represents the water saturation, and n is called the saturation exponent. A value of 1.9 or 2.0 is often chosen for this exponent.[4] If a value of 2.0 is used, the water saturation becomes equal to the square root of the ratio of the resistivity of the 100 per cent wet sand to the true resistivity of the sand. This may be expressed as follows:

$$S = (R_o/R_t)^{1/2} \quad \ldots\ldots\ldots\ldots \quad (3)$$

This relationship has two important applications:

1. If the true resistivity of a particular sand can be determined from an electric log, and if the resistivity of this sand when it is 100 per cent wet can be determined from another log in the area, the water saturation of the sand shown on the first log may be calculated by taking the square root of the ratio indicated above. This method is subject to the following assumptions which are not always justified:
   (a) It is assumed that the physical characteristics of the sand and its interstitial water are the same at the two locations;
   (b) It is assumed that the exponent 2.0 applies and that the sand is free of argillaceous material.
2. If the resistivity in the top portion of a very thick sand is high, and the resistivity in the bottom portion is low, the water saturation in the top portion may be obtained by taking the square root of the ratio of the-e two resistivities. This method is subject to the following assumptions which are not always justified:
   (a) It is assumed that the true resistivities may be determined from the electric log.
   (b) It is assumed that the resistivity in the bottom portion of the sand represents the resistivity at 100 per cent water saturation.
   (c) It is assumed that the physical characteristics of the sand and its interstitial water are the same in the upper and lower portions of the sand.
   (d) It is assumed that the exponent 2.0 applies and that the sand is free of argillaceous material.

In making decisions on a basis of electric log calculations it important to know the assumptions that have been made and be prepared to judge their probable degree of applicability. The assumption 1(a) and 2(c), noted above, imply that the physical characteristics of the sand are the same at two different positions. From Equation (1), it is apparent that this condition will be fulfilled to the extent necessary for these calculations, if the formation factor is the same at the two positions. This in turn will ordinarily be true if the porosity of the sand is the same at the two positions, since formation factor is primarily a function of porosity.

The resistivity of the 100 per cent water saturated clean sand, R_o, is by Equation (1) equal to the product FR_w. Substituting this value for R_o in Equations (2) and (3) they become:

$$R_t = FR_w S^{-n} \quad \ldots\ldots\ldots\ldots \quad (2a)$$

$$S = (FR_w/R_t)^{1/2} \quad \ldots\ldots\ldots\ldots \quad (3a)$$

Equation (3a) is applicable in those instances in which both F and R_w are known and in which R_o may or may not be directly obtainable from the electric log.

The value of F may be determined from laboratory measurements on cores obtained in the sand under consideration. The value of the interstitial water resistivity may be determined from water obtained in a drill stem test provided the amount of water recovered is sufficient to be representative of the uncontaminated formation water. Representative interstitial water samples may also be obtained from wells that are producing exclusively from one zone and which yield some water.

Equation (2a) is fundamental and indicates that a high value of true resistivity may be due to three basic causes:

(1) High F factor — (low porosity - "tight" formations)
(2) High value of R_w — (fresh water)
(3) Low value of S — (presence of oil or gas)

It is very important to understand this thoroughly and to be aware of these three factors when evaluating highly resistive intervals on the electric log.

Equation (2), expressing the resistivity of a clay-free sand in terms of its 100 per cent water saturated resistivity and the water saturation, demonstrates a convenient rule of thumb. A productive oil sand that produces little or no interstitial water usually has a water saturation of less than 50 per cent. Equation (2), with $n = 2$, indicates that such a sand has a resistivity of more than four times its resistivity when 100 per cent water saturated. The rule of thumb is consequently that an oil sand usually has four times or more the resistivity of the same sand fully saturated with the same interstitial water. A 25 per cent water saturation would of course result in 16 times the resistivity. It is important to emphasize that the above rule of thumb applies to sands that are free of clay and for which the saturation exponent value of two applies.

The preceding discussion concerning the relationship between water saturation and resistivity indicates the great necessity of obtaining as much data as possible on the nature of the interstitial water and the value of the formation factor of individual sands in oil productive horizons. A knowledge of the values of R_w and F is of great importance to electric log interpretation.

The Exponent n in the Resistivity-Water Saturation Equation

No relationship has yet been found between the water saturation exponent n and porosity or permeability. Equation

(2) is empirical and, as previously stated, it has been found that a value of 1.9 or 2 for n will often give a good relationship between water saturation and resistivity. There are, however, a few observers who have found that the value of n may differ appreciably from the value of two.[8] There is even some evidence that a value as high as 4.3 may apply.[10]

The following demonstrates the error that may be introduced into a calculation of the water saturation due to an incorrect value of n:

Saturation Exponent	Water Saturation
n	S
1.5	22%
2.0	32%
2.5	40%
3.0	46%

For: R_w = 2.0 ohm-m
and, R_t = 20.0 ohm-m

The rather discouraging aspects of obtaining an answer that may vary to the extent indicated in the above tabulation is at once apparent and makes it desirable to consider what exactly should be expected of the electric log. For instance, if it could be determined with a reliable degree of accuracy that a particular 100-ft sand body, as revealed on the electric log of an exploratory well, had a water saturation of between 20 and 50 per cent, it would readily be admitted that the electric log had performed a useful function. The sand would obviously be formation tested and, if necessary, casing would be set to make the evaluation. This again shows that a properly coordinated use of all of the testing and logging methods is necessary. The electric log is often used in exploratory drilling as a means either to justify, or not justify, the cost of further and more diagnostic testing.

It is important to point out that in development drilling there is little excuse for discrepancies such as indicated above. Cores taken in the producing horizon may be analyzed and values of the water saturation exponent determined. Furthermore, resistivity values as obtained from electric logs may be compared with capillary pressure water saturation data obtained in the laboratory.

One of the problems that remains to be solved is the nature of the dependency of the water saturation exponent n on the physical characteristics of the sand. It is even possible that the empirical relationships between resistivity and water saturation that have been established may not be in the best possible form. An analytical, rather than an empirical, development of a relationship between resistivity and water saturation is highly desirable but has not been obtained. Investigation in this direction offers a fertile field for the theoretically inclined researcher.

The Effect of Clay in Sands

It has been demonstrated experimentally that sand which contains an appreciable quantity of clay shows a different electrical behavior than the same sand when free of such material and that the total conductivity of a clayey sand is comprised of the conductivity due to the interstitial water together with the conductivity due to the presence of wetted clay.[11] It is further demonstrated that the definition of formation factor previously given is valid only for sands that are relatively free of clay. For the general case, in which a sand may or may not contain such conductive material, it is necessary to define the formation factor as the ratio of the resistivity that a sand would have when fully saturated with a brine solution to the resistivity of the brine solution were none of the solid material conductive. The conductivity of a sand saturated 100 per cent with a brine solution may thus be written:

$$C_o = C_c + C_w$$

where C_o = total conductivity of the 100 per cent saturated sand
C_c = conductivity due to the wetted clay
C_w = conductivity due to interstitial water not associated with clay

In terms of resistivity, which is the reciprocal of conductivity, this becomes:

$$1/R_o = 1/R_c + 1/FR_w \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

It is apparent that if the wetted clay is assumed to be nonconductive (*i.e.*: R_c infinite) this relationship reduces to Equation (1) which is applicable to clean sands that are free of argillaceous material.

The recognition of the new term R_c complicates to some extent the laboratory measurement of formation factor since two unknown quantities must be found rather than one. It is possible, however, by saturating a core sample with a very concentrated brine solution, to make the conductivity due to the interstitial water considerably larger than the conductivity due to the presence of clay. In such an instance, the first term on the right-hand side of Equation (4) becomes insignificant with respect to the second term. The formation factor can then be obtained simply by dividing R_o by R_w.

Much remains to be learned concerning the effect of clay on the electrical behavior of fully and partially water saturated sands. The following points are offered as a practical guide to assist in understanding these effects until more quantitative information is available:

1. The electrical resistivity of an oil sand is considerably reduced when argillaceous material is present.
2. The rule of thumb, previously referred to, and which states that the resistivity of an oil sand is four or more times greater than the resistivity of the same sand when fully wet, must be modified when considering clayey sands. Clayey sands may show an increase of only two or three times the resistivity of the fully wet sand.
3. A decreased value of self-potential on the electric log opposite a sand may be due to the presence of clay. Although the presence of clay may sometimes be detected in this manner, it is only a qualitative indication since reduced self potential may also indicate a change in the formation interstitial water salinity.
4. A decreased value of the apparent resistivity as indicated by the short spacing two-electrode curve opposite a salt water sand will sometimes be indicative of the presence of such a sand.
5. The calculation of the water saturation may suffer an appreciable error unless it is known that the sand does not contain clay, or unless a satisfactory method is employed to correct for the presence of the clay.
6. A rather "poor looking" sand on the electric log should not be overlooked on the premise that it is wet due to its low resistivity. It may be a productive oil or gas sand that contains an appreciable quantity of clay. All possible clues which might reveal the presence of clay should be noted.
7. Although the relative occurrence of clay in oil producing sands is not known with any degree of accuracy, it appears that this effect must be taken into account in a considerable number of instances.

Interstitial Water Saturation of Oil Sands

It may be demonstrated experimentally that as oil is gradually caused to replace the interstitial water from a sand originally 100 per cent water saturated, the water saturation will gradually diminish until it reaches a low value beyond which

it is not significantly reduced, even though the pressure on the displacing fluid is increased considerably. Comparison of these minimum water saturation values with water saturations determined from cores taken in oil base fluid, indicates that a somewhat similar displacing mechanism has probably been effective in the accumulation of oil in sub-surface formations. When a reservoir with such a minimum water saturation is produced, little or no water will flow since the easily removable water has previously been displaced.

The water that remains in an oil sand, and is so strongly attached to it, adheres to the surface of the grains and in the small interstices by capillary attraction. The amount of water retained in an oil sand depends to a large extent upon the permeability of the sand. A high permeability sand retains much less water than a low permeability sand. The water retained in commercially productive oil sands will vary from approximately 10 to about 60 per cent.

The dependency of the amount of retained water on the permeability of the sand may be qualitatively understood when it is considered that the specific surface ordinarily increases with decreasing average particle size. Since the latter implies decreasing permeability, it becomes apparent that more water will be retained on the increased surface of low permeability sands.

The conclusion to be reached from the above considerations is that high permeability oil sands will show higher electrical resistivity than low permeability oil sands because the high permeability sand will contain less water and more oil. For a given porosity the higher permeability will result in greater reserves, due to the lower water saturation. In this way it becomes apparent how electric logs are useful in estimating reserves.

That permeability is very important in determining the resistivity of an oil sand, becomes clear when one considers that the resistivity of a clay-free sand is inversely proportional to a power of the water saturation. High permeability oil sands are consequently more easily detected on the electric log than low permeability oil sands since they have considerably greater resistivities, other factors remaining the same.

The resistivity of 100 per cent water saturated sands, commonly called "wet" sands, does not depend to any great extent on permeability because the resistivity of such a sand is given by the product FR_w in which F is primarily a function of porosity and is to a much lesser degree influenced by the permeability. Since the porosity of a sand varies less than the permeability, water sands will usually give a flatter appearing resistivity curve than oil sands.

The quantitative determination of permeability from electric log data has been considered[12] and it is indicated that it may be possible to estimate a lower limit to the average formation permeability from the connate water saturation and formation factor as computed from the electric log data. In development drilling, however, formation factor is determined from cores taken in the producing sand in which case permeability can also be directly measured. Consequently, there is little need for attempting to determine permeability from the electric log when cores must be used to make this interpretation. If no other information is available except an electric log, such as is sometimes the case in exploratory drilling, it is not believed that the formation factor can be determined from the log with sufficient accuracy to warrant its further use in attempting to calculate a minimum permeability.

THE POTENTIAL CURVE OF THE ELECTRIC LOG

The potential curve or SP curve, as it is often called, has universally been used to distinguish sand from shale. In the light of newer concepts, it is more correct to say that it distinguishes shale from nonshale formations. The idea that SP was primarily an indicator of permeability grew in popularity as a consequence of the fact that many geologic sections are composed almost solely of sands and shales. In such a geologic section the nonshale formations are all sands and all relatively permeable; hence, the potential curve indirectly became correlatable with permeability. The older premises still find general application and are of considerable value provided it is understood that exceptions to such reasoning may frequently occur.

It has been established that electric currents exist in the mud column in the vicinity of sand-shale contacts. The potentials produced in the drilling fluid by these spontaneous currents may be measured by suitable devices. The potential variations recorded in this manner comprise the potential curve of the electric log. Such a curve shows that at a sand-shale contact the drilling fluid opposite the sand is negative with respect to the drilling fluid opposite the shale. It is thus deduced that in the vicinity of the sand-shale contact electric current flows in the mud column from the shale towards the sand. The total current flowing in the mud column at the sand-shale contact is often of the order of a few thousandths of one ampere.

Consider a sand lying between two very thick shales. The electric current in the mud column, at the top of the sand, is in a downward direction. At the bottom of the sand the current is also in shale-to-sand direction so is upward in direction. Thus as the logging electrode enters the sand from the top, it attains a negative potential at the boundary due to the drop in electric potential encountered there. Nothing alters this situation until the electrode leaves the sand at the lower boundary where it encounters an oppositely directed electric potential drop in the drilling fluid. Since the conditions there are equal but reversed, the potential curve returns to its shale line on the log. Since only changes of potential are indicated on the curve, there is no zero line for this recording. The shale line is usually conveniently situated a short distance from the edge of the recording tract.

It was indicated at an early date[13] that the potential difference measured in the drilling fluid, when moving the measuring electrode across a sand-shale boundary, is to a great extent a result of the contrast in the ion content of the formation water and the drilling fluid. Opposite shallow fresh water horizons, where little difference exists between the drilling fluid resistivity and the formation water resistivity, a very flat curve is obtained. The verifies the hypothesis that differences in the electrical characteristics of the formation water and drilling fluid have a great deal to do with establishing the spontaneous potentials observed in a well bore.

Much research has recently been devoted to obtaining a more exact explanation of the nature and origin of the electromotive forces that are responsible for the potential phenomenon.[14,15] Considerable effort has also been expended in establishing sound principles of interpretation of the potential curve of the electric log.[16] It is believed that the results of these studies have increased considerably the ability of the engineer or geologist to use the potential curve of the electric log to better advantage. Although both porosity and permeability are indirectly involved in the potential phenomenon, it is realized that the relationship is not simple and involves many other factors.

The presence of appreciable quantities of shale or clay in sands causes a reduction in the magnitude of the potential curve. Silty sands thus have a smaller SP development than clean silt-free sands. This behavior has recently been discussed in some detail.[17] It was indicated above that the potential

curve may qualitatively be considered to differentiate between shale formations and non-shale formations. The reduced development opposite clayey sands and sandy shales conforms to this concept since a shaley sand is less in contrast to a shale than a clean shale-free sand. Since shaley sands are generally less permeable than clean shale-free sands, it is once again apparent why a relationship between permeability and potential was both natural and easy to imply.

If a thick sand is oil or gas bearing in its top portion and fully water saturated in its bottom portion, it will often be noticed that the SP curve is slightly less developed opposite the upper part of the sand than opposite the lower portion. This reduced value of potential opposite part of a sand is frequently used to assist in establishing the possible presence of hydrocarbons in a formation. This effect is noticed primarily in formations containing quite saline interstitial water, and is believed to occur chiefly in formations that contain an appreciable amount of shaley material.[7] The presence of such a reduction of SP, however, does not furnish proof that a sand is hydrocarbon bearing.

It was stated above that electric currents have been detected in the drilling fluid in the immediate vicinity of sand-shale boundaries, and that these currents usually flow in a direction toward the sand. Consider a shale overlying a sand. Upon entering the portion of the mud column opposite the sand, the electric current diverges outward and flows into the sand; then upward and across the sand-shale interface into the body of the shale. It then flows toward the mud column and enters it above the sand-shale contact to begin again its downward descent in the mud column toward the sand. The electric currents thus form a circulating vortex type of distribution in the neighborhood of the shale-sand contact. The path of current flow thus includes as constituent parts (1) drilling fluid, (2) filter cake on sand face, (3) water in the invaded zone, (4) formation water in the sand, (5) shale, and (6) drilling fluid. The SP current distribution is shown in Fig. 1.

In order for electric current to flow in the ground, as described above, it is necessary that electromotive forces exist at one or more points along the path. This is analogous to the statement that the flow of fluid in a porous medium is a result of forces that act to produce a pressure differential in the medium.

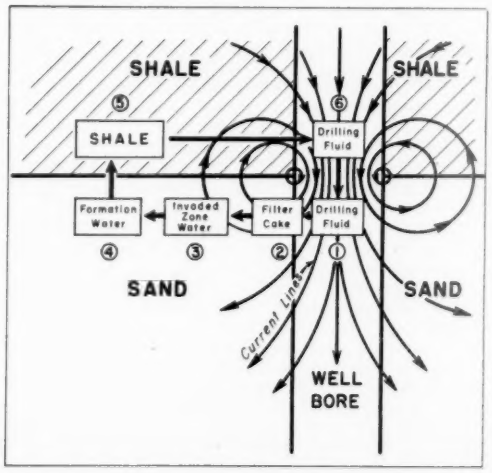

FIG. 1 — THE SP CURRENT DISTRIBUTION AT A SAND SHALE CONTACT.

There is good reason to believe that three sources of electromotive force exist in the system under consideration. They are:

(1) The liquid boundary potential
(2) The shale potential
(3) The streaming potential

These three sources of potential give rise to the electric currents that are detected in the mud column and formations in the vicinity of sand-shale contacts. The nature of these potential sources will now be discussed.

Liquid Boundary Potential

Theory has established that an electromotive force exists at the contact of two solutions differing in their electrochemical characteristics. Such a contact exists between the drilling fluid filtrate in the invaded zone and the interstitial formation water. Since this contact is represented by phases (3) - (4) of the current circuit described above, it is logical to assume that this electromotive force will contribute in establishing current flow. The potential so established is called the liquid boundary potential and is, with certain provisions, proportional to the logarithm of the ratio of the electrical resistivities of the two solutions.[8]

Shale Potential

It has been demonstrated experimentally that if a piece of solid shale be interposed between two solutions differing in their electrochemical properties, the potential difference between the two solutions is often greater in magnitude than the liquid boundary potential that would occur between the two solutions in the absence of the shale barrier. Such a series of phases occurs in the current path considered above and is represented by the elements (4), (5), (6), *i.e.*, formation interstitial water, shale and drilling fluid. The potential that is established in this manner may, for simplicity, be called the shale potential. It is presently believed that the shale potential is ordinarily responsible for a large portion of the total SP effect. Like the liquid boundary potential, the shale potential has been shown, with certain provisions, to be proportional to the logarithm of the ratio of the electrical resistivities of the two solutions that are in contact with the shale.[9]

Streaming Potential

If drilling fluid filtrate, or other similar electrochemical solution, is caused to flow under pressure through a semipermeable membrane, such as a drilling fluid filter cake, an electric potential difference becomes established across the membrane. In this case only a single solution is involved in contrast to the liquid boundary and shale potentials in which two solutions are involved; the other being the formation interstitial water. The potential developed in this manner may be called streaming potential since it is produced by the streaming of a fluid through a semipermeable membrane. Since a considerable pressure differential normally exists across the filter cake opposite a sand, a significant streaming potential will be developed in this manner in the well bore. Since the filter cake constitutes phase (2) of the current circuit previously discussed, the streaming potential contributes to the total SP effect. A quantitative laboratory study of streaming potential phenomena has recently been made, with the result that an empirical relationship has been derived for this effect.[10]

Quantitative Use of the Potential Curve

It was indicated previously that in order to be able to make the best possible interpretation of the electric log, it is neces-

sary to know the resistivity of the formation interstitial water. Much of the research concerned with well bore potentials has been initiated with the primary object of finding a way to determine this quantity from the potential curve. Although it is possible in some instances to determine the resistivity of the formation water, it is not believed advisable, at the present state of development, to place any marked degree of confidence in the preciseness of this determination in the general case. The accurate calculation of formation water resistivity from the potential curve depends upon the degree of validity of several assumptions. Some of these assumptions are:

1. It is assumed that the streaming potential can be made either inconsequential or can be determined so that its effect can be subtracted from the total SP, leaving that portion of the total potential from which the formation water resistivity is calculated.
2. Certain assumptions concerning the electrochemical nature of the drilling fluid and interstitial water must be made in order that the theoretically derived equations may apply.
3. It is assumed that the electric potential drops occurring in the formations are small in comparison to the ohmic potential drop occurring in the mud column. The total electromotive force of the SP phenomena is then closely determined by measurements made in the well bore.
4. It is assumed that the effect of clay in sands can be taken into account when determining formation water resistivity from the SP curve.
5. It is assumed that the sand is sufficiently thick to allow the SP curve to attain its maximum development.

It has been suggested that the resistivity of the drilling fluid be lowered, by the addition of salt, to approximately the value of resistivity of the interstitial water in the more interesting group of formations. It is claimed that this would minimize the value of streaming potential so that a more accurate determination of interstitial water resistivity could be obtained. There are, however, several undesirable features of such a practice. They are:

1. Highly conductive drilling fluid results in poor resistivity curves.
2. The addition of appreciable quantities of sodium chloride to the drilling fluid is in most instances undesirable.
3. A highly conductive drilling fluid column would result in a redistribution of the ohmic potential drops in the sand-shale-mud column system. Such a redistribution would be in a direction to increase the percentage of the total ohmic drop taking place in the formations.

There is little doubt that the precision of quantitative SP methods, for the determination of formation water resistivity, will increase with further development and research. A word of caution is advisable, however, against the tendency to develop a sense of security and confidence in the results of theoretical relationships that have not had a chance to prove themselves fully dependable in field application.

THE POSSIBILITY OF DETERMINING WATER SATURATION USING ONLY THE POTENTIAL AND RESISTIVITY CURVES

From what has preceded it is apparent that three factors are generally essential to making a determination of water saturation from the electric log. These factors are (1) Knowledge of the resistivity of the interstitial water, (2) knowledge of the formation factor, (3) Knowledge of the clay characteristics of the sand.

Factors (2) and (3) are ordinarily determined from cores, and factor (1) is determined by measuring the resistivity of a sample of formation water. Lacking these data the quantitative interpretation of the log usually becomes qualitative in nature. It is, however, interesting to consider what can be done with only the electric log, and with no information concerning formation factor, water resistivity or clay characteristics.

There is little question concerning the desirability of determining water saturation from electric log data alone. A great advantage would be obtained, particularly in exploratory drilling, where interesting horizons that were not cored frequently show up on the electric log. For many years an avenue of approach to such a goal has been apparent. The reasoning involved is briefly:

1. Determine the formation water resistivity from the potential curve.
2. Determine the formation factor from a measurement of the invaded zone resistivity. (This will be discussed more fully.)
3. From (1) and (2) determine the resistivity of the fully wet sand (*i.e.*, $R_o = FR_w$).
4. Using this value of R_o in Equation (2), calculate the water saturation of the formation from the value of true resistivity as determined from the electric log.

Step (2) involves determining the resistivity of the drilling fluid filtrate and the resistivity of the invaded zone. If then, the invaded zone could be assumed to be 100 per cent saturated with drilling fluid filtrate, the formation factor would be given by the ratio of invaded zone resistivity to the drilling fluid filtrate resistivity. Unfortunately, there are several reasons why such a simple method cannot be used, at least at the present time, for the determination of formation factor. Some of these reasons are:

1. If the formation contains oil, the invaded zone will not be 100 per cent saturated with drilling fluid filtrate.
2. No accurate means is presently available for determining the resistivity of the invaded zone. There is, however, good reason to believe that such techniques may be developed.
3. If the formation is impermeable, there is no invaded zone. Proceeding on the basis that one exists would give an erroneous answer.
4. There is the possibility, in at least some instances, of the mixing of interstitial water and drilling fluid filtrate, by ionic diffusion or otherwise, to produce a fluid in the invaded zone different than drilling fluid filtrate.

Aside from these obstacles there are certain questions which arise concerning the overall method. Some of these questions are:

1. How accurately can the true resistivity be determined from the electric log?
2. How accurately can the interstitial water resistivity be calculated from the potential curve?
3. Can the effect of clay on the determination of true resistivity, formation water resistivity, and invaded zone resistivity be adequately taken into account?
4. How accurately can the interstitial water saturation be determined from Equation (2)? What is the value of the saturation exponent n?

On a basis of the present state of knowledge of the petrophysical behavior of rocks and electric log interpretation in general, it may be said that the answers to these questions indicate that the calculation of water saturation from strictly electric log data alone is subject to so many assumptions that it is at best only a qualitative evalution which, however, may still be of great value from the practical viewpoint.

The Electric Log and Exploratory Drilling

The determination of water saturation from strictly electric log data alone, as discussed above, becomes necessary when

little is known concerning the nature of the formation interstitial water, porosity, formation factor, and clay characteristics of the various horizons. This is frequently the case in exploratory drilling. Fortunately, however, in this case even a qualitative evaluation of water saturation is of considerable value. As mentioned previously, if it could be determined that a particular 100 ft thick sand, as revealed on the log of an exploratory well, had a water saturation of between 20 and 50 per cent, it would ordinarily be considered entirely economic to set casing if this were necessary to test the sand adequately.

In exploratory drilling we are hunting for new oil and gas fields. The stakes involved are so great that it is entirely undesirable and unwise to attempt to place all of our confidence in any one formation evaluation tool. It is only through a coordinated use of coring, testing, and logging methods that economic exploratory drilling may be achieved.[1] The purpose of the electric log in exploratory drilling is to single out those more promising appearing formations for further evaluation. In this respect it fulfills a tremendously important need. As the quantitative methods improve in accuracy, it will be possible to single out more efficiently those formations exposed in an exploratory well that are most likely to yield oil or gas.

Over the course of years as electric log interpretation methods become more quantitative and less qualitative, more confidence will be instilled in those who apply them. As this occurs, exploratory drilling will require less coring and testing. This process, however, is slow and it is important that overconfidence is not placed in new techniques until their degree of reliability has been established.

The Electric Log in Development Drilling

Once an oil producing horizon has been found, and the probable extent of production estimated, a program for the development of the field is designed. This program should include coring of the productive horizons in a selected number of strategically situated wells. If a particular horizon is a sand or sandstone, the following core analysis measurements should be made: (1) porosity; (2) permeability; (3) formation factor; (4) clay analysis; (5) capillary pressure water saturation (experimentally determined so that it approximates the saturation in a virgin oil or gas reservoir sand); (6) residual water saturation (saturation in a core as recovered from the well bore); and (7) residual oil saturation (saturation in a core as recovered from the well bore).

If any water is obtained during a drill stem test, or along with produced oil, it should be analyzed immediately for ion content and electrical resistivity. Such tests should be made in every instance possible, and the values of water resistivity catalogued for each of the producing horizons. Information concerning formation water characteristics is not only valuable in electric log interpretation but also in tracing the origin of waters produced from the well.

When a few wells have been cored and analyzed in the manner described above, the electric logs can then be used in a quantitative fashion in completing the remaining wells in the field. In this manner the full advantage of the quantitative technique may be obtained. In a sense, the core analysis and water data are used to calibrate the electric log readings.

Cores from the producing sand horizons may be sent to the laboratory and the relationship of resistivity and water saturation determined. This eliminates the errors that may otherwise be introduced by clay effects or improper choice of water saturation exponent.

It should be noted, however, that even in this optimum condition for the use of electric logs in a quantitative manner an evaluation of hole effect, invasion effect, and bed thickness effect must be made in order to obtain the true resistivity. This implies that best accuracy will be obtained in thick beds in which invasion is not too deep.

Fractured Formations

Certain formations having a nongranular type of porosity have been found to be oil and gas productive. Typical of this class are fractured shales, cherts, limestones, and vuggy limestones. Combinations of vuggy, fractured and intercrystalline limestone may also occur.

Electric logs lose much of their diagnostic value in formations of this sort. When analyzing an electric log made in an exploratory well, the first question to be answered is: What type of formations are represented on this electric log? It is partly in order to answer this question that coring, sidewall sampling, and drilling fluid analysis are employed.

When the drill bit encounters a highly fractured formation in which the oil and gas exist only in the fractures, it is entirely possible to have very serious and deep invasion of the drilling fluid into the formation fissures. This has a tendency to drive the oil and gas back into the formations making them very difficult to detect by any means whatsoever. In this case, the fluorescence of the drill cuttings may be the only evidence of hydrocarbons that is obtained.

REVIEWING AN ELECTRIC LOG

When an electric log has been obtained, there is a strong tendency to examine the curves immediately and then proceed to make decisions concerning the fluid content of the various horizons depicted on the log. Although this may in some instances be excusable, a much better procedure is to consider in detail other factors related to the log before examining the curves. The more important of these factors are indicated by means of the following questions:

1. What is the resistivity of the drilling fluid and the diameter of the hole? A qualitative estimation should be made of the effect of the drilling fluid on the resistivity curves and on the SP curve.
2. What type of drilling fluid has been used in drilling and logging the hole? Some types of drilling fluid affect the SP curve adversely, and some types affect the resistivity curves adversely. This matter should be clarified before examining the curves. Low water loss fluids will often result in a smaller invaded region. This is frequently reflected in the reading of the small spacing resistivity curve.
3. What scales have been employed in recording the resistivity curves and the SP curve? The absolute value of the resistivity is related to porosity and water saturation. It is necessary to know the ohm-meters of resistivity in order to properly evaluate the formations. It is advisable to check that there are no scale changes between the end of the log and the portion being examined. The value of the SP deflection above the shale line is related to the type of formation water.
4. How did the depth measurements made by the logging service company check the depth measurements made by the drilling crew?

When these factors have been considered, a more effective examination of the curves will result.

When examining the electric log curves recorded opposite a particular horizon, it is necessary to consider the length of time that the formation has been exposed to the action of drilling fluid. It is also necessary to take into consideration all available data pertaining to the physical and chemical nature of the formation and its fluid content. Such additional data is furnished by drilling fluid analysis logging, sidewall samples, cores, or formation tests.

When comparing electric logs, it is necessary to compare the conditions under which the logs were made. This implies a comparison of the spacings employed, mud resistivities, scales, and types of drilling fluid. If an electric log is very old, it is necessary to consider the changes in the reservoir conditions that may have occurred due to subsequent depletion. In this regard it is interesting to note that since the high resistivity portions of an oil sand are often the most permeable, it is possible that these portions will yield water first as edge-water encroaches.

SUMMARY

1. In development drilling, a quantitative determination of the water saturation of sands and sandstones may be made from the electric log. This requires, however, that the formation factor and the formation water resistivity are known. A knowledge of the clay content and its effect on the electrical behavior of the sand is also necessary. The determination of water saturation becomes unreliable in thinly interbedded sand-shale sections. Coring of the productive sand in selected wells is desirable in order to determine formation factor and clay characteristics.
2. In exploratory drilling the electric log assists in singling out those formations that show evidence of containing oil or gas. These formations can then be evaluated by the more diagnostic formation testing methods. When examining exploratory well logs, great caution should be exercised in order not to miss any possibly productive horizons of a fractured nature. Under exploratory drilling conditions, the electric log interpretation often becomes quite qualitative in nature, but is still of considerable value in the overall formation evaluation program.
3. Past and present research and development have improved our ability to make a good electric log interpretation. It appears that further research in the field of petrophysics and further development of electric logging systems will increase the accuracy of the quantitative methods. It is probable that improved logging methods will make possible a more accurate determination of formation factor from invaded zone measurements. Further research may provide a more precise method of determining formation interstitial water resistivity from the potential curve. It is important that the results of research be adequately and thoroughly tested in the field before placing too much confidence in them.

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REFERENCES

1. Walstrom, J. E.: "Optimum Use of Various Testing Methods in Exploratory Wells," API *Drill. and Prod. Prac.*, (1950) 79.
2. De Witte, L.: "Resistivity and Saturation Distribution in Invaded Zones of Porous Formations," *Oil and Gas Jour.*, (July 27, 1950) **49**, 246.
3. Tixier, M. P.: "Electric Log Analysis in the Rocky Mountains," *Oil and Gas Jour.*, (1949) **48**, 143.
4. "Resistivity Departure Curves," Schlumberger Document No. 3, (1949).
5. Keller, G. V.: "An Improved Electrode System for Use in Electric Logging," *Producers Monthly*, (Aug. 1949).
6. Doll, H. G.: "The Laterolog: A New Resistivity Logging Method with Electrodes Using an Automatic Focusing System," *Trans.* AIME, (1951) **192**, 305.
7. Archie, G. E.: "The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics," *Trans.* AIME, (1942) **146**, 54.
8. Archie, G. E.: "Introduction to Petrophysics of Reservoir Rocks," AAPG *Bull.*, (May 1950), 956.
9. Dunlap, H. F., Bilhartz, H. L., Shuler, E., and Bailey, C. R.: "The Relation Between Electrical Resistivity and Brine Saturation in Reservoir Rocks," *Trans.* AIME, (1949) **186**, 259.
10. Guyod, H.: "Electric Logging Developments in the U.S.S.R.," *World Oil*, (Aug. 1948), 120.
11. Patnode, H. W., and Wyllie, M. R. J.: "The Presence of Conductive Solids in Reservoir Rocks as a Factor in Electric Log Interpretation," *Trans.* AIME, (1950) **189**, 47.
12. Wyllie, M. R. J.: "Theoretical Considerations Involved in the Determination of Petroleum Reservoir Parameters from Electric Log Data," Third World Petroleum Congress, The Hague, Netherlands, May 28-June 6, 1951, Section II, Preprint 3.
13. Schlumberger, C. and M., and Leonardon, E. G.: "A New Contribution to Subsurface Studies by Means of Electrical Measurements in Drill Holes," *Trans.* AIME, (1934) **110**, 273.
14. Wyllie, M. R. J.: "A Quantitative Analysis of the Electrochemical Component of the SP Curve," *Trans.* AIME, (1949) **186**, 17.
15. Wyllie, M. R. J.: "An Investigation of the Electrokinetic Component of the Self Potential Curve," *Trans.* AIME, (1951) **192**, 1.
16. Doll, H. G.: "The SP Log: Theoretical Analysis and Principles of Interpretation," *Trans.* AIME, (1949) **179**, 146.
17. Doll, H. G.: "The SP Log in Shaley Sands," *Trans.* AIME, (1950) **189**, 205.

DISCUSSION

By M. E. Loy, Schlumberger Well Surveying Corp., Los Angeles, Calif., Member AIME

The interpretation of well logs is a skill which can be developed only with practice. The established interpretative techniques discussed by the author, as well as the refinements now in the progress of development, are subject to the effects of several variable formation characteristics. Very often, assumptions must be made as to the exact degree of these effects on each individual case, and the computed results weighed in the light of the probable accuracy of the necessary assumptions. This process of assuming and weighing can be highly successfull, but practice and experience are necessary. Quite often it will be found that even though assumptions have to be made, the conclusions will be quite definite.

The complex nature of the factors governing the relations between well logs and the petrophysical behavior of rocks suggests that this study is a full-time job. Many organizations are developing well logging specialists within their ranks. This is proving to be successful, but these specialists cannot be everywhere at once; consequently, they are valuable as consultants and final review authorities for the exploration geologists, development engineers, production engineers, reservoir engineers, etc. It still remains that every individual who can benefit by the use of well log information should be capable of analyzing these logs.

We urge you, then, to attempt to use all the interpretative methods and to determine for yourselves the range of reliability for the various methods under all conditions. This is necessary in order that you may develop, with practice, the experience needed to be best guided by a full use of the data available from well logs.

DISCUSSION

By C. C. Liedholm, Signal Oil and Gas Co., Los Angeles, Calif., Member AIME

The field engineer, or geologist, must be able to interpret the results of the many methods now available for evaluating the fluid content of a formation. Consequently, he cannot always devote the time and study required to keep abreast of the latest evaluation techniques for electric logs. Most development engineers have recognized the factors which influence the resistivity values recorded by the electric log and have by comparison evaluated zonal saturation in a purely qualitative manner. The quantitative methods introduced in the last few years for evaluating saturation may have sometimes been confusing, particularly when the answer conflicted with the engineer's intuitive determination. Walstrom's paper shows that there can be a meeting ground between the two outlooks —that a quantitative approach can be used to supplement the purely qualitative outlook. Conversely, the limitations on a quantitative determination due to uncertainty in some of the variables used can be examined to advantage by qualitative methods. Walstrom's careful use of approximate limiting values makes the transition from one approach to the other natural and reasonable.

Walstrom states that the electric log is primarily intended to determine the fluids in a formation and not what will come out of a formation. If we are concerned only with conventionally spaced resistivity curves, this is true in most cases. However, the use of short spacing resistivity measurements to detect the presence or absence of mud cake has proved to be of considerable value in determining the ability of a formation to conduct fluid. In areas with high resistivity pay, these short spaced curves make it easier to determine whether or not something will come out of the zone than to evaluate what is in the zone. In development drilling the approximate zone pressure is generally known, and in exploratory drilling pressure can be assumed to be near the original. Consequently, assuming that the zone is not filled with immovable tar, an approximation of a formation's ability to give up fluid can be made with presently available electrical logging equipment. I would like to ask Walstrom why the use of these short spaced curves were omitted from his paper.

DISCUSSION

By Loy M. Charter, Shell Oil Co., Los Angeles, Calif.

Electric log interpretation, either quanitative or qualitative, truly is a combination of an art and a science. As stressed by Walstrom, all petrophysical data obtainable must be utilized, not only to supplement the electric log interpretation, but in the actual interpretation of the electric log itself. Needless to say, the more supplemental data available, the better will be the interpretation, but there always is an economic optimum. We have found that adequate electric logs, including special devices such as MicroLogs, focusing system logs, etc., together with interval cores, sidewall samples, and possibly formation tests, and continuous ditch samples, cutting analyses if representative, drilling speeds, etc., usually are sufficient to allow quite reliable evaluations of the fluid saturations of most possible reservoir formations. The instances of formations that are not evaluatable from such data usually are determinable, and additional means such as additional sidewall samples or testing can be resorted to if economically justified.

As pointed out by the author, the determination of precise formation resistivities often is difficult and sometimes impossible because of bore hole, invasion, and adjacent bed effects. A quantitative approach even under the more difficult conditions usually will result, however, in at least a valid qualitative evaluation. As discussed by Walstrom, mud filtrate invasion and adjacent beds are the primary perturbing effects that make determinations of true resistivities often difficult and sometimes impossible. Their effects often can be minimized, however, by logging at frequent intervals. Their effects also can be evaluated by comparing overlapped portions of logs and rerunning questionable intervals. In very high resistivity intervals such as limestones where bore hole, invasion and adjacent bed effects have been a real bugaboo, our limited experience to date indicates that the newer focusing logging systems are a tremendous improvement over conventional logging systems under these conditions. It might be well to stress here that the conventional, self-potential and resistivities are only three forms of numerous systems now available, and it would be to the benefit of the industry to build up an experience as rapidly as possible with other applicable forms of electric logs, term them what you will.

We grant that formation factors are not always determinable from electric logs, but we have found that with a reasonable amount of supplemental data they can be determined rather reliably in most cases. If the various resistivity curves indicate different resistivities after correction for bore hole and adjacent bed, but not invasion effects, the resistivity of the invaded zone usually can be approximated if some supplemental data for calibration is available and adjacent bed effects are not too severe. We have found that the MicroLog often assists in making this approximation. From this invaded zone resistivity the formation factor usually can be approximated, by assuming if necessary a residual hydrocarbon saturation in the invaded zone. If, however, there is a possibility of very viscous oils, this technique breaks down since estimations of residual oil effects then are not reliable. In this case, though, ditch samples and/or sidewall samples should show the presence of the viscous oil.

It is pointed out that the determination of the fluid saturations is dependent on the values of the saturation exponent "n" which has been reported to vary appreciably. This is a problem that is perennial. In extensive laboratory work we have found that the value of the exponent "n" does vary from sample to sample, even within a sand body and with samples of comparable porosity and permeability. The average, though, when sufficient data are available, is very close to two, as reported by Archie in 1942. Since the responses of the electric log, particularly those of the longer spacings, are necessarily averages from appreciable formation volumes, it is the average value of "n" which appears rather constant, and not individual values, with which we should be concerned.

AUTHOR'S REPLY TO MESSRS. LOY, LIEDHOLM AND CHARTER

In the formal comments published above and in some of those received more informally, three criticisms of the paper are made which deserve a closer analysis and a specific rebuttal. These criticisms may be summarized as follows:

1. The conclusions which may be inferred from the paper could create the impression that the ability of electric logging in its present state is more limited than it actually is.
2. The possibility of forthcoming improvements in the response of the electric log is not apparent enough in the paper.
3. Most of the discussion is centered around the determination of water saturation and nothing constructive is said about the determination of porosity and permeability.

Careful examination of these criticisms indicates that they are basically not a question of correctness or incorrectness,

but concern the manner in which the author has judged the relative merits and demerits of electric log interpretation. In other words, the comments indicate dissatisfaction with the slightly conservative tinge that the author had injected into the paper. The author wishes it to be understood that every word in the paper, and every possible implication that might be made from the phrasing, were carefully considered. His reply to these criticisms is summarized in the following paragraphs.

For the last five years, the author has been associated exclusively with an oil producing organization. In this time he has not only had the opportunity of studying electric log interpretation in detail, but has had the opportunity of appraising the relationship of the electric log to the overall economics of discovering and producing oil. A primary function of an oil producing company is to find oil and to produce it economically. Electric logging, although an important phase of this work, is only a small part of it.

Although it is desirable to get as much information as possible from the electric log, this information must be correct. The stakes involved are too great to be concerned with seeing how far one can stretch an electric log interpretation and probably be correct. There are other tools of evaluation that may be used to complement the electric log findings when there is any doubt. A very real problem concerning the electric log interpretation, however, is to know when there is doubt and when there is not. If there is any chance of doubt, one should then use every other possible means to evaluate the particular formation correctly.

When drilling an exploratory well, one is greatly concerned with the security of the investment and the success of the venture. For this reason there is a tendency to be very careful in all steps of the operation. In particular, one must be cautious in reaching conclusions on the basis of the evidence provided by the various logging and testing methods. It is perhaps better that a petroleum engineer be over cautious and make an unnecessary drill stem test, than over confident of his ability to interpret an electric log and miss an oil field.

It must be remembered that the author stated at the beginning of the paper that it was "directed not so much to the logging or research specialist, as to the petroleum engineer and geologist." A reasonably conservative philosophy has been employed in the paper because it is considered best.

The second of the above three criticisms indicates that the author has not emphasized sufficiently the possibilities of forthcoming improvements in the response of electric logs. We must bear in mind that the principal purpose of the paper was to point out the utility which the engineer or geologist can derive from the log delivered to him today. This course of presentation was decided upon since the petroleum engineer or geologist is more interested in what can be done with his present logs than what may be possibly done with them in the future. This latter is a responsibility that rests more directly with the electric logging service companies.

In order to indicate something of the developments that tomorrow may bring, the author does discuss the determination of *F*-factor from wall resistivity measurements and the determination of formation water characteristics from the SP curve. This is emphasized in part (3) of the summary of the paper.

Thus, contrary to what some may believe, the author's opinion is that he has placed sufficient emphasis on what may come in the future — at least he has indicated the possible direction that such developments may take. It is best not to be over-optimistic in what these improvements will do for us until they have proven themselves. We have been mistaken before.

The author purposely avoided any emphasis on the quantitative use of electric logs in limestone formations — particularly in exploratory drilling. Generally speaking, the electric log loses much of its diagnostic value in this type of rock and other means of formation evaluation should also be employed. For a more detailed discussion of this phase of exploration, the author refers to his paper entitled "Optimum Use of Various Testing Methods in Exploratory Wells," which appears in the 1950 edition of the API *Drilling and Production Practice*.

The author's experience with MicroLogs indicates that although the MicroLog may show the presence of porosity, the porosity may not be sufficient for commercial production. On the other hand, vuggy porosity or fractured porosity in limestone or similar rocks — sufficient for commercial production — may not be evident from the MicroLog. Thus, although a useful tool, one must interpret the MicroLog with caution. It is best to depend on the fluorescence of drill cuttings and upon drill stem testing in exploratory wells penetrating limestone formations. This is a practical and straightforward approach to the problem. In a secondary degree one may place confidence in the neutron and MicroLog techniques.

The author is familiar with the special and experimental techniques that are being developed for the determination of porosity and permeability from electric log data alone. He also believes, however, that these techniques are not yet reliable — particularly as they apply to exploratory operations. In development operations, opportunity is ordinarily afforded to determine porosity and permeability in a reliable manner from cores taken in a selected number of development wells strategically situated throughout the field. For these reasons, the author decided against placing more emphasis on these techniques than he has already done in his paper.

In exploratory operations the determination of the oil and gas saturation of the various formations is of most importance. This is indirectly determined from the electric log by determining the water saturation and subtracting it from unity. For this reason emphasis was placed on the determination of water saturation. If in an exploratory well a good oil saturation is determined from the electric log for a particular horizon, the formation is ordinarily tested exhaustively to determine its productive ability, despite any speculation concerning the porosity and permeability.

It is well to mention that what the author has incorporated into his paper is partly the result of the study of a tremendous amount of core analysis data and careful watching of production results and drill stem test data. In addition, the results of a very considerable amount of basic research on electric log interpretation have, although not referred to directly, influenced the manner in which the author has appraised the present state of electric log interpretation.

The author believes that his appraisal of electric log interpretation methods is neither pessimistic nor over-optimistic. He believes it is reasonable.

In conclusion, the author again states that the criticisms of his paper primarily concern the degree of reliability with which he describes the present state of electric log interpretation. The author's approach is the more cautious. The opinions of those commenting upon the paper are of interest to the author and he hopes that his thoughts may be stimulating to them. ★ ★ ★

The Drift of Things

. . . as followed by EDWARD H. ROBIE
Secretary AIME

Overtime for Engineers

Many engineers are currently working harder than usual, in part because of the demands being made upon them for increased production in the war effort, and in part because engineers are in short supply so that there is more to do for those who are available. In some instances the question has come up as to what additional payment, if any, should properly be made for overtime work, and to what extent is such payment legally permitted under the rules of the Salary Stabilization Board.

Most engineers employed in an executive, administrative, or outside salesman capacity are not paid for overtime. They are paid for doing a job instead of for the hours they put in, and are free to do all the unpaid home work they feel they should do after dinner, as well as to do a bit of thinking and worrying during wakeful hours in bed. But engineers employed in a strictly professional capacity normally have standard office hours. Some employers pay for overtime and some don't. Their practice as it existed on Jan. 25, 1951, may be continued. In the absence of such practice at that time, the Salary Stabilization Board says that the engineer may now receive additional compensation up to his straight-time rate for an extended work week. No formal approval of the Board is required. "A professional engineer," as defined by the Board, "is a person employed in a professional capacity who, by reason of his special knowledge of the mathematical and physical sciences and the principles and methods of engineering analysis and design, acquired by professional education and practical experience, is qualified to practice engineering."

New York or Atlantic City?

In which place is it preferable to hold the annual meeting of a professional society like the AIME — New York or Atlantic City? That is, a winter meeting.

Chief advantages of Atlantic City over New York are that technical sessions are better attended, there being little else to do there in winter, the cost to members is less, and hotel facilities are better adapted to a meeting the size of ours. As to cost, take a banquet, for instance. The Chalfonte—Haddon Hall, which caters especially to winter conventions, charges about $7 for a banquet dinner of standard quality. A similar dinner at the Statler in New York would cost about $8.50 and about $10.50 at the Waldorf-Astoria. Rooms, too, are somewhat less at Atlantic City. On the other hand, AIME headquarters is put to some extra expenses for staff travel, food and lodging, and members living in New York and environs are forced to pay a hotel bill. New York, of course, has more varied amusements to offer, plenty of big stores, and the glamor of a big city.

The choice may be discussed at the forthcoming meeting in New York. In the meantime if any reader cares to express an opinion one way or the other we shall be glad to hear it.

Inducted Engineers

A letter from a young man just inducted into the service and fearful that his engineering training is not going to be utilized reached us last week from Fort Riley, Kans. The AIME, cooperating with the other Founder Societies, is doing what it can, through the Engineering Manpower Commission, to see that engineers are not being wasted in the military establishment. So we passed this young man's letter along to T. A. Marshall, Jr., executive secretary of that Commission.

Marshall tells us that the normal procedure now being followed by the Army in handling Selective Service inductees is to have them first complete 16 weeks of basic training before assignment to specialized categories. During that time they are classified. If one has an engineering degree he should be classified as scientific and engineering personnel at the end of the basic training period. He should then be transferred to a technical detachment and assigned an MOS (Military Occupational Specialties) reflecting his education.

If a young man is looking for a commission, it might be added that the current policy in the army is to transfer to OCS (Officer Candidate School) applicants for commissions in the infantry only. The local unit commander can give information on this point, based upon the aptitude shown in tests. In view of the current shortage of engineers, it is believed that a young man should seriously consider remaining in enlisted status unless he can obtain a commission in a branch of the service that can make full use of his technical skills. His work may thus be more to his liking even if his uniform is not.

Fireside Incident

The mistress of the house, who was napping in the living room the other evening, suddenly woke up enough to inquire, "What's that noise?"

"I am merely," we told her, "tearing out some of the advertising pages in the last issue of *Life* in order to get at the reading matter and pictures."

"That's silly," she said, "and anyway, you shouldn't be one to object to advertising, for that pays part of your salary, and you are always saying that that's what you need more of."

"But our kind of advertising is different. For one thing, it's not all mixed up with the leading articles to distract the reader's attention. And for another thing, it contains a lot of useful information and news about the latest developments in machinery which, if we were an operating man, it would be in our interest to read.

"Now take these 42 pages we have just torn out. Fifteen of them, or more than one third, are advertising liquor."

"Since when have you ceased to have any consuming interest in liquor," we were queried.

"Since our cupboard became well stocked," we replied. "And we don't believe that these brands are necessarily noted for their quality. For instance, six pages are devoted to advertising mixtures of whiskey with from 60 to 70 per cent of alcohols, though you would never guess it from the ad. The word 'alcohol' is never mentioned once. Then there are four pages of cigarette advertising, and it must be ten years since we smoked a cigarette. And if we did take up the habit we doubt if the advertisements would give us much of a clue as to which one we like best."

"I think I'll go back to sleep. That is, if you are through tearing paper."

So we stopped, and while we were thinking about the matter, browsed through the advertising pages of ME, JM, and JPT, as we call them for short. We didn't find them in the middle of an article, and we found them interesting and instructive. The next time we meet an operating engineer, we believe we can talk to him a little more intelligently. ★ ★ ★

TOOLS

ADVANCED...HIGHLY-SPECIALIZED

one of many reasons why

HALLIBURTON'S *best*

for your DRILL STEM TEST!

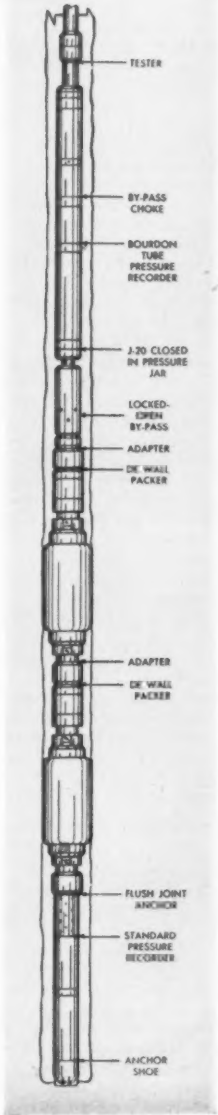
You want your test to be right on the first run—and *Halliburton can do it!*

Misruns are rare with Halliburton because of its advanced, highly-specialized testing tools. The Halliburton string has many exclusive features developed by 25 years grass-roots research and improved by the enormous experience of servicing over a million wells.

For example, Halliburton has a new curved J-slot that automatically locks every tool. It prevents valves from opening too soon and permits the tool to automatically close and positively lock simply by raising the drill pipe a few feet.

Other exclusive features include the Bourdon Tube Pressure Recording Device, special-duty packers to meet various hole conditions, locked open By-Pass, surface controlled adjustable chokes and the multi-purpose circulating valves. These last two features also provide a greater degree of safety and a better control of the well when high pressures are met.

Constant improvement in tools and technology enables Halliburton to maintain its leadership and keep pace with the ever-changing requirements of the oil industry. No matter how deep the well, how high the pressures or temperatures, Halliburton can give you a successful test. Avoid excessive misruns, let Halliburton make your next test! Halliburton Oil Well Cementing Company, Duncan, Oklahoma.



MORE REASONS WHY HALLIBURTON'S best!

GREATER ACCURACY IN PRESSURE RECORDING
The Bourdon Tube Pressure Recording Device, exclusive with Halliburton, gives you far greater accuracy at no extra cost.

25 YEARS RESEARCH BACKS UP YOUR TEST
Halliburton alone offers a testing service developed and improved by 25 years of energetic, grass-roots research.

YOU GET REAL PERSONAL SERVICE
Your Tester stays on the rig from start to finish of your test, giving you his full-time attention during this highly important operation.

YOU'RE ONLY MINUTES AWAY
Halliburton has hundreds of highly-trained Testing Specialists experienced in every type of well. One of these Testers is only minutes away.

YOU'RE SURE IT'S AVAILABLE
Each Halliburton Tester is completely equipped with the latest tools and ready to go as soon as you call. Phone him before you come out of the hole.

HALLIBURTON *YEARS AHEAD IN DRILL STEM TESTING!*

Junior Member Age Limit Raised for Veterans

Ordinarily, applicants for Junior Membership must not have passed their 30th birthday anniversary at the time their application is received by the Institute. By recent action of the Board, however, a credit of one year on this entrance age limit is given for each year of military service. A similar credit is given veterans in changing their status from Junior Member to Associate Member or Member, which must normally be done before their 33rd birthday anniversary. Heretofore, these credits were extended only to veterans of World War II; now, *all* veterans are given this privilege. ★ ★ ★

Members Receive Awards For Outstanding Papers

Winners of three AIME awards, to be presented at the forthcoming Annual Banquet, were announced at the Nov. 14 meeting of the Executive and Finance Committees.

C. G. Dunn, F. Lionetti, F. W. Daniels and M. J. Bolton will each receive the Mathewson Gold Medal Award for the following series of three papers on grain boundary energies: "The Effect of Orientation Difference on Grain Boundary Energies," by Dunn and Lionetti; "Measurement of Relative Interface Energies in Twin Related Crystals," by Dunn, Daniels and Bolton; "Relative Energies of Grain Boundaries in Silicon Iron," by Dunn, Daniels and Bolton.

Donald A. Dahlstrom is the winner of the Rossiter W. Raymond Award for his paper entitled "High-Speed Classification and Desliming with the Liquid-Solid Cyclone."

G. Derge, W. O. Philbrook and Kenneth M. Goldman share honors in the Robert W. Hunt Award for their paper, "The Mechanism of Sulphur Transfer Between Carbon-saturated Iron and CaO-SiO_2-Al_2O_3 Slags." Each will receive a silver medal and certificate.

At the Dec. 5 meeting of the Board the winner of the J. E. Johnson, Jr., Award, was announced: William R. Bond, vice-president, Operations, Lone Star Steel Co., "for his contribution to the blast-furnace art in developing a smelting practice for the successful utilization of East Texas ores."

At the same meeting, winners of the Tenth Annual Student Prize Paper Contest were announced as follows:

Undergraduate prizes of $100 each: Charles R. Rainsalo, Carnegie Institute of Technology, for his paper, "The Tensile Properties of an Aged 31 Per Cent Cr-Fe Alloy." Alfred F. Weinberg, Illinois Institute of Technology, "Age-hardening of Copper-Beryllium Alloys." William E. Bond, Carnegie Institute of Technology, "Some Properties of Silver-Copper Alloys Made by Powder Metallurgy."

Graduate prize of $100: John F. Radavich, Purdue University, "A New Electrolytic Stripping Technique." No other graduate prize will be given.

The awards will be a feature of the Welcoming Luncheon at the Annual Meeting. ★ ★ ★

Slate of Nominees Declared Elected for 1952

No other nominations having been received, the ticket named by the Committee on Nominations for AIME Officers in 1952 was declared elected at the November meeting of the Executive and Finance Committees. Names and biographical data were published in the July issue of THE JOURNAL OF PETROLEUM TECHNOLOGY: President, M. L. Haider; President-elect, Andrew Fletcher; Vice-Presidents, O. B. J. Fraser and J. B. Morrow; Directors, C. H. Benedict, R. B. Caples, T. B. Counselman, T. L. Joseph and C. E. Reistle, Jr. ★ ★

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Proved in over 1,500 installations throughout the world, the space-saving economics of the Accelator is but one of the many advantages thoroughly described by Infilco Bulletin 1823. Write for your copy today.

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FIELD ENGINEERING OFFICES IN 36 PRINCIPAL CITIES

World's Leading Manufacturers of Water Conditioning and Waste-Treating Equipment

Petroleum Branch Officership Eligibility List

ARTICLE VIII of the By-Laws adopted March 20, 1947, provides that:

". . . To be eligible for election to the Executive Committee a member shall have had wide experience in the affairs of the Branch . . ."

". . . To be eligible for Chairman a member shall have three years of active service in the Branch, at least one of which shall have been as Chairman of a standing or special committee or as a member of the Executive Committee . . ."

". . . To be eligible for Vice-Chairman a member shall have had two years of active service in the Branch, at least one of which shall have been as chairman of a standing or special committee, or as a member of the Executive Committee, or a Chairman of a Local Section . . ."

The list below is of members who meet the specific provisions of eligibility for election to Chairman or Vice-Chairman. No attempt has been made to distinguish those who meet the non-specific portion of the eligibility requirements, i.e., "wide experience" and "three years of active service." Data after each name represent the year and type of service, according to the code below.

The Pacific Petroleum, Wyoming Petroleum and Illinois Basin Chapters have been considered Local Sections, within the intent of the By-Laws. The list may be incomplete with respect to the earliest years of the Branch (1922-1927), as full records on that period are not available. Please call any errors or omissions to the attention of the editor.

POSITION CODE

AC	Associate Branch Chairman	PP	Chairman, Papers and Programs
BT	Branch Treasurer	PR	Chairman, Production Review
Ch	Branch Chairman	Pro	Chairman, Progress
CLS	Chairman, Local Section	Prod	Chairman, Production
EC	Member, Executive Committee	PT	Chairman, Production Technology
Ec	Chairman, Education	Pub	Chairman, Publications
Eco	Chairman, Economics	RE	Refinery Engineering
EE	Chairman, Engineering Education	RVC	Branch Regional Vice-Chmn.
ER	Chairman, Engineering Research	SC	Chairman, Special
Ge	Chairman, Geophysics	ST	Branch Secretary-Treasurer
Lc	Chairman, Lucas Fund	St	Chairman, Stabilizing
Me	Chairman, Membership	TC	Chairman, Technology
Nom	Chairman, Nominating	TE	Transportation Engineering
PE	Chairman, Production Engineering	VC	Branch Vice-Chairman
PG	Chairman, Production Geology		

Akins, D. W., Jr. — CLS 47
Alcorn, I. W. — Me 45 CLS 44 Ch 48 EC 48-49 Nom 49
Ambrose, A. W. — CLS 27 EC 30-35 Ch 28
Andrews, Paul — CLS 49 EC 49 VC 50
Armstrong, E. B. — CLS 47
Atkinson, Burton — CLS 48 Me 50
Atkinson, Thomas — CLS 47
Aucoin, Riley — CLS 45
Beal, Carlton — EC 46 ST 46 VC 48 EC 48 SC 47-48
Beams, Robert J. — CLS 48
Beardmore, H. F. — CLS 41 RVC 44 Ch 46 EC 45-46-47
Beecher, C. E. — AC 30 Ch 31 EC 32-37
Beesley, Jack H. — Me 51
Bell, John S. — PE 46 CLS 44 EC 51
Bennett, E. O. — EC 35
Berlin, E. W. — PR 51
Berwald, Wm. B. — CLS 45, EC 47
Bethancourt, Raoul — CLS 49
Blau, L. W. — Ge 43-44
Bradley, R. J. — Ec 48-49
Brown, Bob Diggs — CLS 51
Brown, W. F. — CLS 50
Brownscombe, E. R. — Pub 48
Buckley, S. E. — CLS 42 PP 42 EC 44-45-47-48-49 AC 44
Bugbee, J. M. — Me 43 CLS 43 Pub 51
Calhoun, J. C., Jr. — EC 49-51
Camp, R. W. — RE 32
Carter, D. V. — PR 50
Churchwell, R. M. — CLS 50
Coberly, C. J. — AC 40 EC 41-42
Coburn, R. W. — CLS 51
Cooley, H. M. — CLS 50
Corless, G. B. — EC 37-38-39 Ch 38
Covell, K. A. — CLS 38 PE 44
Craft, B. C. — Ec 45 ST 38-39-40 EC 44 PP 44 EC 48-49 50
Crichton, Jack A. — CLS 51
Dahlgren, E. G. — PR 47-48-49
Decker, Harold — CLS 47 EC 49-50-51
Dooley, David L. — CLS 47
Duce, J. Terry — Prod. 35-36-37-38-39-40-41
Dunlap, E. N. — CLS 49
Earlougher, R. C. — CLS 46 Pub 47 EC 50-51-52
Elkins, Lincoln — CLS 49 VC 51
Elkins, Lloyd — CLS 45 VC 47 EC 47-49-50 Ch 49 Nom 50
Estabrook, E. L. — EC 32
Field, J. H. — CLS 51
Fisher, Eugene A. — CLS 46
Fisher, Gordon H. — CLS 47 Pub 49
FitzGerald, Norman D. — Ec 42-43-44
Fitzgerald, P. E. — CLS 40 ER 42 Me 44 Pub 46 VC 48 EC 48
Fohs, F. Julius — Ch 25-26
Fowler, Harry C. — ER 32 EC 36
Frick, Tom C. — CLS 47-49 EC 51
French, Richard W., Jr. — PT 48 VC 50 Ch 51
Garrison, A. D. — ER 41
Gaylord, E. G. — EC 35 Nom 39
Geis, W. H. — AC 38 EC 39-40-41 Ch 39
Gill, John D. — EC 45-46
Gilmore, R. B. — BT 50
Gouldy, Roland — CLS 50
Granberry, R. C., Jr. — CLS 50
Graybeal, J. W. — CLS 45
Greenidge, S. M. — EC 39
Griswold, E. H. — PE 31-32
Haider, M. L. — PE 38 Pub 43-44 EC 43-45-46 Ch 45 Nom 46
Halbouty, M. T. — CLS 39 Me 40
Hamilton, R. G. — CLS 43
Hamman, Cecil A. — CLS 49
Hammond, John P. — CLS 49
Harlan, Don L. — CLS 49
Haynes, W. P. — Prod 43-44
Hayward, J. T. — ER 36
Herald, Frank A. — Prod 33-34
Heithecker, R. E. — BT 51
Heroy, W. B. — EC 39-40-41-43
Hess, Robert M. — CLS 45
Higgs, Morton T. — CLS 45
Hill, H. H. — ER 30
Hocott, Claude R. — PP 45 AC 46 EC 46
Holmes, Joseph A. — CLS 47
Huntington, R. L. — ER 37-38
Jackson, Warren J. — CLS 48
Jones, N. N. — CLS 41
Kantzer, Basil — CLS 51
Katz, D. L. — ER 39-40 PP 43 Ed 46-47
Kaveler, H. H. — ER 45 PP 46 EC 46
Kelly, R. B. — EC 37-42 AC 41
Keplinger, C. H. — CLS 37 PE 42 RVC 46 EC 46
Kingman, D. G. — CLS 51
Kipp, Earl M. — TC 51
Knappen, Russell S. — EC 32-34
Knowlton, D. R. — EC 38-41
Kraus, Edgar E. — PG 47
Krause, H. M., Jr. — CLS 51
Langford, C. M., Jr. — CLS 40
Leeton, H. B. — CLS 50
Lehnhard, Phil J. — CLS 50
Leonard, W. W. — CLS 51
Lilley, E. R. — ST 30 Pub 45
Little, W. N. — CLS 50
Loomis, A. G. — ER 44
Love, R. W. — CLS 50
Lovejoy, John M. — Ch 27 LC 32-33-34-35
Lund, Richard J. — EC 51
Lyle, Henry — CLS 48
Manian, Peter P., Jr. — Me 47 CLS 48
Mapes, Clarel B. — EC 33-34
Marsh, H. N. — EC 32-33-36-37-38 Ch 36 Nom 40
Marshall, Dan L. — CLS 47
McCutchin, John A. — CLS 42
McGirl, J. N. — CLS 51
McMillan, John — CLS 47 EC 50-51
Mercier, V. J. — CLS 49
Millikan, C. V. — Ch 30 EC 33-36-40 Nom 38
Moore, Jack M. — CLS 51
Moore, T. V. — ER 35 PE 37 AC 39 Ch 40 EC 41
Morris, W. S. — CLS 40 PP 40-41 EC 43-44-45 AC 42 Ch 44 Nom 45
Moulton, Gail F. — Prod 45-46 VC 49
Murrell, John H. — CLS 46 VC 47 EC 47-48-49-50
Muskat, Morris — PT 50
Naramore, Chester — EC 44-45
Nowels, K. B. — ER 33
Nye, George L. — CLS 48
Ogden, L. A. — CLS 35
Parks, Ernest K. — CLS 45
Parks, Mercer H. — CLS 46
Parsons, B. E. — EC 34
Petree, Ernest L. — CLS 50
Pishny, Charles — CLS 45
Pollard, Terry A. — Me 48 ER 49
Pogue, J. E. — Ec 27 Ec 32
Porter, L. E. — PE 43
Porter, W. W. II — CLS 47 EC 47-48
Posgate, James — CLS 48
Power, H. H. — PE 34 EC 35-36-40-51 Ch 35 Me 37 Nom 41 Ec 43-44
Powers, W. D. — CLS 50
Putnam, Murray — CLS 50
Pyle, H. C. — Ch 47 EC 47-48 Nom 48
Reistle, C. E., Jr. — EC 42 AC 43
Rhea, A. S. — CLS 42
Schultz, Paul — Eco 50
Sheldon, Dean H. — CLS 48 EC 49-50-51
Shepherd, Jack M. — CLS 49
Sherborne, John E. — ER 46 EC 47-48-49-51 SC 46-47 VC 49 PT 49 Ch 50
Simmons, Fred E., Jr. — CLS 50
Sinsheimer, Warren A. — EC 30-34
Smith, Roy H. — CLS 50
Smith, Veleair C. — AC 43
Spice, W. H. Jr. — CLS 51
Spoor, H. C., Jr. — SC 49
Stephenson, Eugene A. — PE 32 ST 33-37 inc., EC 34-39-40-41-42-43 PP 38 Ch 41
Stolz, Harry P. — AC 41 Ch 42 EC 43 Pro 45
Struth, H. J. — EC 32-47
Suman, John R. — EC 32-33-34
Swensrud, Sidney A. — Ec 35-36-37-38
Teague, J. U. — CLS 41
Terry, L. F. — EC 39-40-41
Thornton, Owen — CLS 49 VC 50 Pub 50
Thronson, Lee J. — CLS 51
Trostel, E. G. — ER 43 PE 45 CLS 45
Turnbull, Paul — CLS 47 VC 51
Umpleby, J. B. — PE 27 Ch 29 EC 32-47 SC 46
Uren, Lester C. — Ed 48
Vance, Harold — PP 39 EC 41-42 ST 43-44
Vietti, Wm. V. — CLS 37 EC 47-48
van Wingen, N. — PT 47 CLS 50
Walker, A. W. — CLS 39 PE 41
Waddill, Alfred W. — Me 46 CLS 51
Warner, C. A. — CLS 38 Me 39-41 AC 42 Ch 43 EC 44 Pro 46
Wasson, H. J. — EC 35 Prod 32 EC 35
Waszkowski, Henry — CLS 50
Watson, C. P. — AC 43 Prod 30
Weaver, P. — EC 39 Me 42 Ge 45-46
Wilcox, Stanley W. — CLS 44
Wilde, H. D., Jr. — PE 33 EC 33-34-35 Ch 34
Wrather, W. E. — EC 33-34 Ch 33
Wright, J. K., Jr. — CLS 51
Yates, G. L. — CLS 51
Young, C. M. — EE 32-33
Zavoico, Basil — Prod 42 AC 43 RVC 43

Synthetic Fuels

Continued from Page 17, Section 1

money and manpower to move into a field that is so decidedly uneconomic. The development of synthetic fuel manufacturing should follow a normal course under straight forward economics," Schultz concluded.

NPC Estimate of Economics of Coal Hydrogenation Plant, Rock Springs, Wyo.

Yearly Expenses, millions of dollars	
Operating expense	53.8
Depreciation	24.8
Subtotal	78.6
Credit for by-products and other credits	18.9
Cost of gasoline before profit or interest on debt	59.7
Net interest on debt	
Return on investment @ 6%	32.0
Federal income taxes @ 50%	32.0
Cost of gasoline including return	123.7
Cost/gallon	$ .41

Financial Analysis and Return on Investment as Estimated by USBM, Coal Hydrogenation Plant, Rock Springs, Wyo.

		Millions of Dollars Per Year
Total value of products		73.6
Operating expense	34.9	
Depreciation	15.3	
Cost of operating ex profit and interest		50.2
Gross profit		23.4
Interest on funded debt (3½%)		8.6
		14.8
Average interest income		4.3
		19.1
Coal depletion allowance		1.5
Taxable net income		17.6
Income taxes @ 50%		8.8
Net income		8.8
Coal depletion allowance		1.5
Net funds available		10.3
Net funds as per cent of equity capital*		6.2

*USBM return on investment is based on a 6 per cent annual return on 40 per cent equity capital. The remaining 60 per cent is to be borrowed at 3½ per cent interest.

To AIME Members Who Have Not Paid 1952 Dues

AIME dues are payable Jan. 1 of each year. Copies of the journals are sent regularly for the first three months of the new year pending receipt of dues. If dues are not received at AIME headquarters by the middle of March, or when the wrappers for the April issues are run off, the member's stencil is removed from the circulation list, and there will be delay in receipt of the April issue. When dues are finally paid, back issues will be supplied only to the extent that copies are available. Duplicate bills should be mailed early in March to those in arrears, and prompt payment at that time, or before, is urgently requested. Resignations, to be accepted as from a member in good standing, must be received before March 31.

Eastman CASING ROLLERS

★ GREATER ECONOMY IN RESTORATION OF DAMAGED CASING.

★ RESTORES collapsed casing and liners to their proper size and roundness.

★ EFFICIENT, EFFECTIVE, AND WIDELY USED.

★ AVAILABLE IN A.P.I. sizes for casings with ID ranging from 3½ to 17⅞ inches. Other sizes specified, made to order.

Call the Eastman Office nearest you. Consult the Phone Directory.

Body and rollers of specially heat-treated steel
Continuous rolling surface minimizes friction and vibration
Roller ends tapered to prevent snagging
Circulation through tool and around each roller

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Employment Notices

The JOURNAL will post notices of men and jobs available. Companies and AIME members are invited to use this space, for which there is no charge. Except as noted below, address replies to: Code (appropriate number), JOURNAL OF PETROLEUM TECHNOLOGY, 408 Trinity Universal Bldg., Dallas 1. Show return address on envelope. These replies will be forwarded unopened and no fees are involved.

Replies to the positions coded M-664-5112, Y6569, Y6560, Y6129, Y5908, Y5640 and Y5532 below should be addressed to: Engineering Societies Personnel Service, 8 West 40th St., New York 18, N. Y. The ESPS, on whose behalf these notices are published here, collects a fee from applicants actually placed.

PERSONNEL

♦ Petroleum engineer, 44, married; seven and one-half years' oil field experience covering geological exploration; drilling, completing and reworking wells; the design and installation of both surface and subsurface equipment; some reservoir work; also field experience with both gas injection and water flood projects. Location preferred, Rocky Mountains. Now available. M-664-5112-E-5-San Francisco.

♦ Engineer, petroleum production, presently employed with major company, desires responsible position with aggressive independent or small producing company; five and one-half years' experience in Gulf Coast area in all phases of production with some experience in reservoir engineering; 30 years of age, married, veteran. Code 159.

♦ Engineer, 27, graduate with three years' experience including drilling, production, water flooding and some reservoir engineering. Desires position with progressive independent or small company. West Texas preferred, but will relocate. Code 160.

POSITIONS

♦ Engineering draftsman with experience, to detail and lay out piping and equipment for oil terminals. Salary, $4,800 a year. Location, New York, N. Y. Y6569.

♦ Safety inspector or safety engineer to assume safety responsibility at a general Army base of shops, refineries and all transportation. Salary, $5,400-$9,600 a year plus 10 per cent for overseas duty. Location, Japan. Y6560.

♦ Geologist to do necessary structural and stratigraphic research to find oil in the district. Location, Texas. Y6129 (b).

♦ Engineers. (a) Oil refinery process design engineer, 30-40, chemical or mechanical engineering graduate, with actual oil refinery distillation process design work on cracking plants or equivalent. Will supervise engineers and draftsmen in the design of all types of distillation units from flow plans and data. Must be able to discuss with oil refinery experts, all phases of oil refinery design. Salary open. (b) Oil refinery field maintenance and construction superintendent, 30-60, with actual experience in the field working for an oil company or for a contractor who has contract work in an oil refinery performing the work listed below. Hiring and supervising all classes of mechanics and assigning them to oil refinery maintenance or construction as required. Salary open. Location, New York metropolitan area or Gulf Coast area, or both. Y5908.

♦ Senior safety engineer, chemistry or chemical engineering degree, with minimum of ten years' experience in safety work in a chemical plant or oil refinery. Salary, $7,200-$9,600 a year. Location, New York, N. Y. Y5640.

♦ Engineers. (a) Petroleum engineer for field operations, 25-35, with degree in petroleum engineering or equivalent and about three to five years' experience. (c) Division safety supervisor, 30-45, graduate, preferably mechanical, with five years' experience in petroleum, drilling and production safety supervision. (d) Junior engineers, recent petroleum engineering graduates, capable of developing under training. Location, Peru, S. A. Y5532. ★ ★ ★

PETROLEUM or RESERVOIR ENGINEER

The Arabian-American Oil Company requires the services of a qualified Petroleum or Reservoir Engineer, proficient in mathematics and with extensive experience in oil and gas reservoir engineering on primary and secondary recovery problems.

Duties will include preparation of basic field production and reservoir data for application in analogue and digital computers, performance of analytical analyses of field behavior and interpretation and preparation of resulting data for reservoir engineering reports on specific fields. To work in Company's New York office.

Write giving personal history and work experience. Please include telephone number.

THE ARABIAN-AMERICAN OIL COMPANY
RECRUITING SUPERVISOR
505 Park Avenue
New York 22, N. Y.

K. C. Heald to Receive Sidney Powers Medal

K. C. Heald, vice-president of the Gulf Oil Corp., Pittsburgh, Pa., has been named to receive the Sidney Powers Memorial Medal of the AAPG. Announcement of the award was made by Frank A. Morgan, AAPG president.

Named in honor of the late Sidney Powers of Tulsa, fourteenth president of the AAPG, the medal will be awarded to Heald "in recognition of his long and outstanding service and contributions in petroleum geology, and for his leadership in research bearing on the important problem of the origin of oil." Presentation will take place at Los Angeles, Calif., March 25, at the joint meeting of the AAPG, the Society of Economic Paleontologists and Mineralogists, and the Society of Exploration Geophysicists.

Only five other petroleum geologists have received this high professional and scientific honor. They are Wallace E. Pratt (1945), Alexander Deussen (1947), A. I. Levorsen (1948), E. DeGolyer (1950), and Max Steinke (1951). ★ ★ ★

Rocky Mountain Fund To Publish New Volume

One of the outstanding special volumes published by the AIME was the Lindgren volume, "Ore Deposits of the Western States," which appeared in 1933. It has been out of print for several years. Consideration has been given to reprinting the volume, either with or without corrections and additions to bring it more nearly up to date. Decision has now been made to publish a totally new volume, again under the sponsorship of the Rocky Mountain Fund, the scope and content of which is to be in the hands of the following committee: John W. Vanderwilt, chairman; Carlton D. Hulin, T. S. Lovering, Charles F. Park, Harrison Schmitt and Philip J. Shenon. ★ ★ ★

Personals

T. W. NELSON has been appointed associate director of Socony-Vacuum's laboratories, effective March 1. Nelson has been director of Magnolia Petroleum Co.'s Field Research Laboratories at Dallas for the past six years. He will make his headquarters in New York and will be responsible for the coordination of research in laboratories at Paulsboro, N. J., Brooklyn, N. Y., and Dallas. A native of Montana, Nelson was graduated from the Colorado School of Mines in 1934 with a degree in petroleum engineering. He worked in the technical department of Socony-Vacuum's refinery at Augusta, Kans., and at the company's Research and Development Laboratories at Paulsboro, N. J., before becoming director of the Dallas laboratories.

Nelson will be succeeded at Magnolia's Field Research Laboratories in Dallas by DAYTON H. CLEWELL, assistant director. Clewell, who received his PhD in physics from Massachusetts Institute of Technology, joined Magnolia in 1938 as a research geophysicist. Four years later he was transferred to the Field Research Laboratories as supervisor of exploration research. In 1946 he became assistant director of the laboratories.

+

KERMIT E. BROWN is now employed by Garrett Oil Tools, Inc., Monroe, Louisiana, as a sales and service representative.

+

SHANNON L. MATHENY has joined the Continental Oil Co., Ventura, Calif., as a petroleum engineer trainee.

+

J. H. Sidwell has resigned from the Hiawatha Oil and Gas Co., San Antonio, Tex., to accept a position with the Imperial Production Corp.

+

W. L. FALCONER has been made managing director of Powder Oil, Ltd., Calgary, Alberta.

DAVID BLAINE WILKIE, JR., has accepted a position with the Venezuelan Atlantic Refining Co. He was previously with the Skelly Oil Co. in the New Mexico district.

+

MAURICE LEWIS, JR., has resigned as exploitation engineer from the Shell Oil Co. in the North Texas and Oklahoma division. He is now district engineer with the British American Oil Producing Co., Midland, Tex.

+

WILLIAM A. VESTAL, Phillips Petroleum Co., has been transferred from Shreveport, La., to Bartlesville, Okla.

+

GEORGE P. ALDEN, formerly with the Barnsdall Oil Co., Tulsa, Okla., is now with the Salmon Oil Corp.

+

WILLIAM A. WHITMIRE is sales engineer for the Regan Forge and Engineering Co., San Pedro, Calif.

LESTER B. SWAN, general manager of United Oilwell Service, S. A., in Caracas, Venezuela, has been named assistant manager of Dowell Incorporated in Tulsa. Before his appointment as general manager of United early in 1949, Swan was district manager of Dowell in New Orleans. Previously he had served in Tulsa as a development engineer. He is a graduate of the University of Tulsa, where he received a degree in petroleum engineering, and was formerly with the Stanolind Oil and Gas Co., production department.

+

FRANCIS M. ELLETSON has joined The Texas Co., New Castle, Wyo., as junior engineer.

Proposed for Membership, Petroleum Branch

Total AIME membership on Nov. 30, 1951, was 17,405; in addition, 2,079 Student Associates were enrolled.

ADMISSIONS COMMITTEE

Thomas G. Moore, Chairman; Carroll A. Garner, Vice-Chairman; George B. Carless, F. W. Hanson, Albert J. Phillips, Lloyd C. Gibson, R. D. Mallison, John T. Sherman. Alternates, A. C. Brinker, H. W. Hitzrot, Plato Malozemoff, Ivan Given, T. D. Jones, W. A. Clark, Jr.

Institute members are urged to review this list as soon as the issue is received and immediately to wire the Secretary's office, night message collect, if objection is offered to the admission of any applicant. Details of the objection should follow by air mail. The Institute desires to extend privileges, but does not desire to admit persons unless they are qualified. Objections on applications should be received on the 15th of the month following publication in PETROLEUM TECHNOLOGY.

In the following list C/S means change of status; R, reinstatement; M, member; J, Junior Member; A, Associate Member; S, Student Associate; F, Junior Foreign Affiliate.

CALIFORNIA

Granada Hills — Klipp, James E. (A).
Long Beach — Powell, Gerald E. (C/S-S-J); Soden, Archie D. (C/S-S-J).
Los Angeles — Bergquist, John F. (C/S-S-J).
Ojai — Brown, Arthur L. (C/S-J-M).

ILLINOIS

Flora — White, Alton O'Neal (M).

KANSAS

Lawrence — Everett, John P. (C/S-J-M).
Wichita — Davis, Tommy C. (M); Stancliffe, Walter Darrell (R,C/S-S-M).

LOUISIANA

Lafayette — Goode, William W., Jr. (C/S-J-M).
Morgan City — Mathis, James W. (J).
New Orleans — Kammler, Albert H. (M); Olivier, Fulton J. (J) (C/S-S-J).
Shreveport — Khoury, George A., Jr. (C/S-S-J); White, J. L. (J).

MASSACHUSETTS

South Acton — Vogenthaler, Thomas J. (C/S-S-J).

MISSOURI

St. Louis — Koederitz, William Arthur (C/S-S-J).

NEW MEXICO

Hobbs — Oberly, Edward S., Jr. (J); Sallee, Warren L. (J).
Lovington — McGouldrick, Jack F. (J).

NEW YORK

Hartsdale — Wilhelm, Oscar (M).

OKLAHOMA

Ardmore — Curtis, Willard L. (R,C/S-S-J).
Ponca City — Murphy, John A. (C/S-A-M).
Tulsa — Davis, J. Gilbert (C/S-S-J); Harder, Hudson O. (M); Weber, Leonard B. (M).

TEXAS

Athens — Crawford, Ronald F. (M).
Beeville — Onstott, Lloyd J. (J).
Bellaire — Murphy, George W. (J).
Corpus Christi — Allen, Fraser H. (C/S-J-M); Cawley, Marion M. (J); Jones, Frank L. (C/S-J-M).
Denver City — Ratts, Robert Vincent (J); Smith, Bowman L. (J).
Fort Worth — O'Shields, Richard Lee (C/S-S-J); Roper, Robert L. (J).
Houston — Adair, William B. (C/S-S-J); Doscher, Todd M. (M); Gilbreath, Merle L. (M); Purcell, William R. (C/S-J-M); Rabensburg, Aubrey H. (M); Seyfarth, Frederick (J); Toma, Abdel W. (J); Wege, John M. (R,C/S-J-M); Zagar, Frank S. (J).
Kilgore — Anderson, John M. (J); Burgess, George W. (R,C/S-S-J); Cook, Audrey M. (R,C/S-S-J); Richards, James P. (C/S-S-J); Tarbel, Brook D. (J).
Luling — Beaver, M. H. (J).
Odessa — Kirk, Rufus P. (M); Tribble, Robert G. (J).
Refugio — Pace, Floyd A. (R,C/S-S-J).
Wichita Falls — Rosenthal, Charles A. (M); Yeager, Hal W., Jr. (J).

WASHINGTON

Vancouver — Greves, John H. (M).

WYOMING

Casper — Griswold, John Anthony (C/S-S-J).

ALASKA

Anchorage — Ryan, Irene E. (R,C/S-S-A).

CANADA

Alberta — Erick-Mulder, Fritho R. (C/S-J-M); Monerief, Charles M. (R,C/S-J-M).

VENEZUELA

Barcelona — Price, William T. (J); Wood, Harry D. (R,C/S-S-M).
Caracas — Grim, George R., Jr. (C/S-J-M).

★ ★ ★

Book Reviews

Magic Oil — Servant of the World

By Alfred M. Leeston. Juan Pablos Books, Dallas, 1952. 237 pp., illus., tables, 9¼ x 6¼ in., cloth, $3.75.

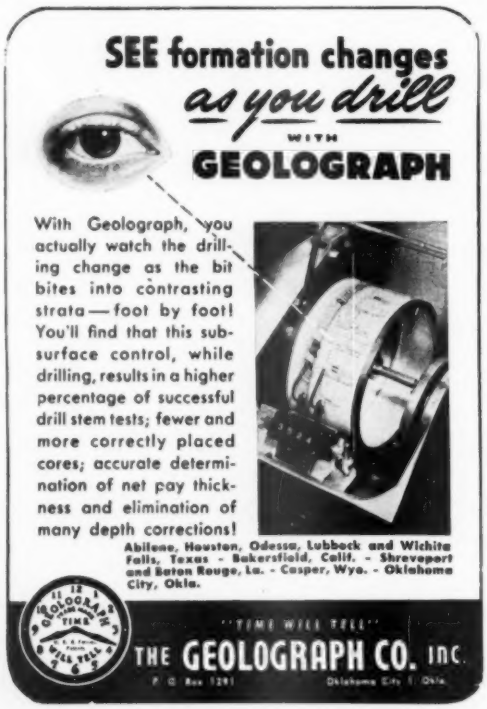
Reviewed by Jack A. Crichton, San Juan Oil Co., Dallas, Tex.

This book offers worthwhile reading to anyone engaged in any phase of the oil business, and to any layman with a curiosity about the petroleum industry.

Dr. Leeston's economic background enables him to make an analysis of the political and economic issues in the United States and in foreign countries that have affected or will affect the petroleum industry. He supplements his theories with a host of facts that could only have been evolved by having at his disposal the excellent petroleum library of Dr. DeGolyer, to whom the book is dedicated. A selected bibliography is included.

The discussion of the political background in the Middle East and Russia that has affected the oil industry in those areas is especially timely. Dr. Leeston's observations of Europe are firsthand, and the result of years of living and studying in the countries concerned.

The book is a valuable contribution to the field of petroleum literature and to the library of the reader who enjoys assimilating knowledge in a pleasant sort of way.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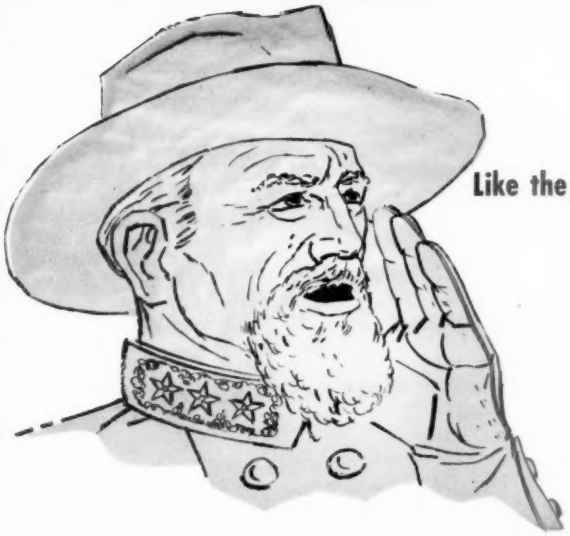

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